Further Experiments on the artificial Production of Snow Crystals*.

By

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(Plates I–X)

1. Introduction.

In the foregoing paper[1] it was stated that almost all sorts of snow crystals could be produced artificially in the cold chamber laboratory, the temperature of which was nearly at $-30°C$. Further experiments in the same line have been repeated with improved apparatus. Paying some technical precautions the authors succeeded to some extent in getting any required sort of snow crystal in a reproducible manner. The relations between the form of crystal and the conditions of its formation were studied in detail with respect to each modification of the apparatus. The results will be described in this paper.

2. Apparatus.

The pieces of apparatus used in this series of experiments were more or less the same in principle as those described in the previous work. They were modified to give different modes of convection of water vapour. In order to get various manners of circulation of air, four sets of apparatus were constructed. Apparatus No. 1 is shown schematically in Fig. 1. Two concentric glass cylinders are held vertically, so that warm vapour is driven upwards inside the inner tube while the cooled air comes down through the space between the two cylinders. The water in reservoir R is warmed electrically as in the previous experiment. Using this apparatus the mode of convection of water vapour seemed to be fairly steady and a certain type of snow crystal could be obtained in an almost reproducible manner under given conditions. The cover C is a metal sheet and D is a plate of cork or ordinary wood. The latter was introduced in order to

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* Investigations on Snow, No. 11.

1) This Journal, Vol. 2, p. 1.

interpose something between the cold metal plate C and the crystal S. This plate D was removed in some cases. The wedge W may be of metal or wood. T_a, the temperature of the air where the snow crystal is made, varies considerably with the thermal nature of the materials surrounding the crystal. Suitable materials were chosen by trial according to the form of crystal to be manufactured. Changing the form of the upper part of the apparatus above the wooden ring W, two modifications of apparatus No. 1 were constructed. They are shown in Figs. 2 and 3. In case of apparatus No. 2, the form of the upper

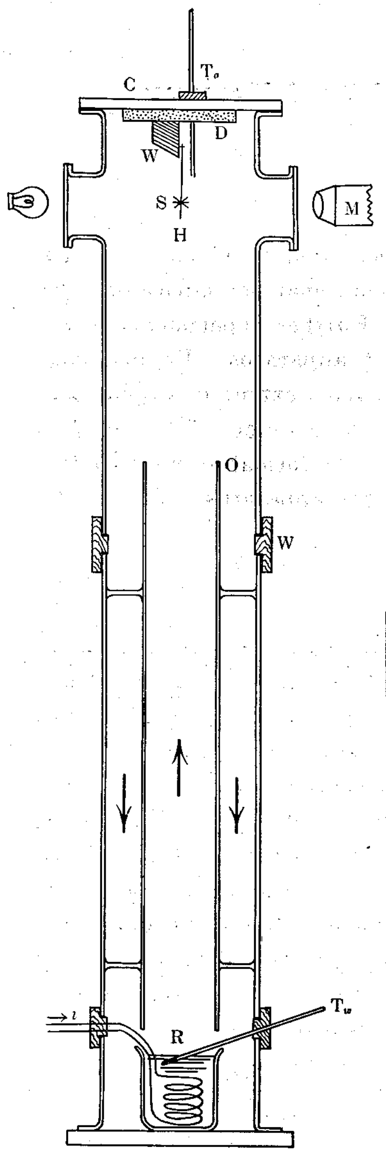


Fig. 1. Apparatus No. 1.

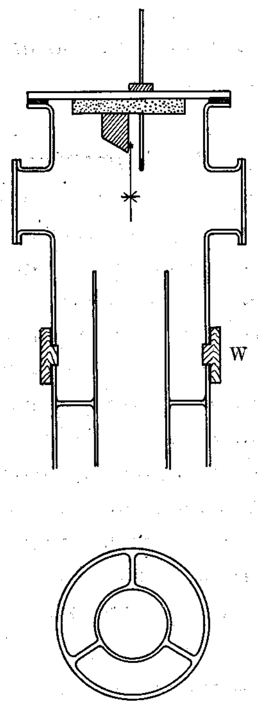


Fig. 2. Apparatus No. 2.

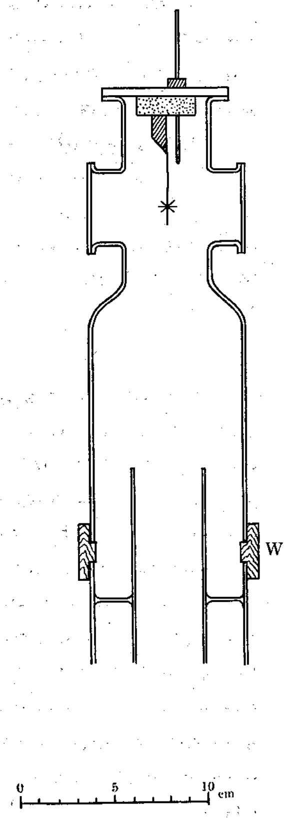


Fig. 3. Apparatus No. 3.

cylinder is the same as that of No. 1, the length of the cylinder being 10 cm shorter. The supply of warm water vapour is in this case more abundant than in the previous case No. 1 and T_a is accordingly higher although the temperatures of the room and the water in the reservoir remain the same. With apparatus No. 3 it was intended to lessen the rate of supply of water vapour to the place where the crystal is made.

Apparatus No. 4 was constructed under a different principle as shown schematically in Fig. 4. With this apparatus it was intended that a circulation of the air current be caused by using two vertical cylinders kept at different temperatures. The ascending air current goes up in the glass cylinder, which is kept warmer than the room temperature by an electric heater carrying a feeble current i'. The outside of the cylinder is wrapped with a piece of felt F. The side tube represented in the figure by a thick line is a copper one. This tube is always kept cold at nearly the same temperature as that of the

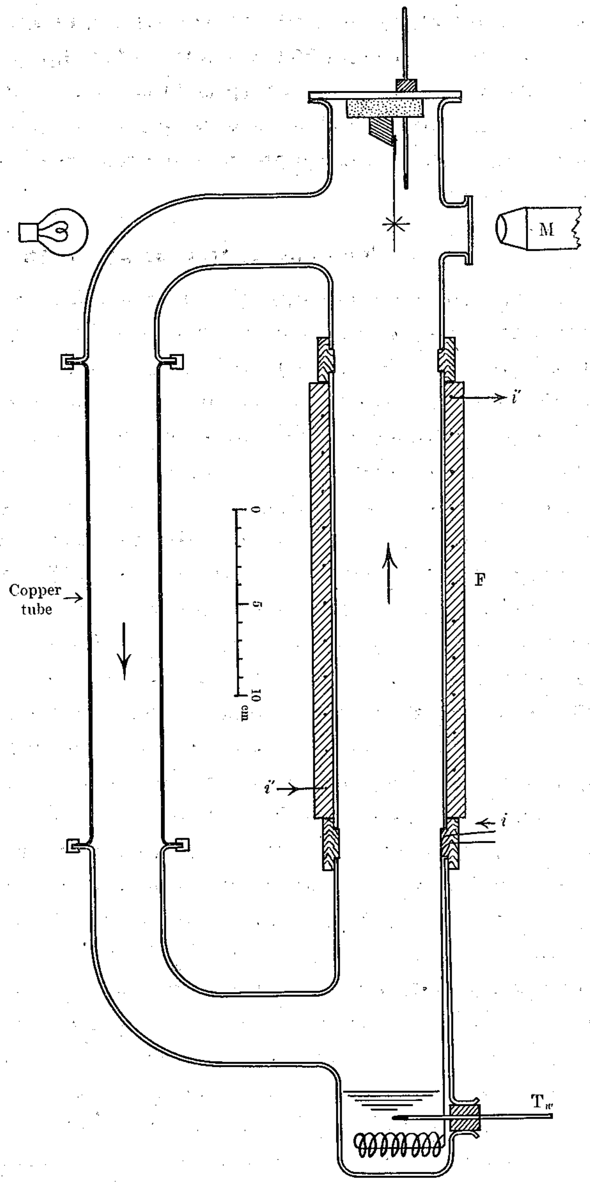


Fig. 4. Apparatus No. 4.

room. It is attached for the purpose of accelerating the downward convection of the air in the apparatus. Adjusting the heating current i', which is in the order of few tenths of an ampere, the rate of convection of air could be made fairly great so that the hair suspending the crystal was swayed about violently by the stream of air. Large fern-like crystals of snow were rather quickly made in this apparatus.

All these four sorts of apparatus were used in a cold chamber of the Low Temperature Laboratory belonging to our University. The experiments were carried out with the room temperature ranging between $-15°C$ and $-45°C$.

3. The convection of air in the apparatus.

The mode of air convection in the apparatus No. 1 was first studied. For this purpose the room temperature T_r and the temperature of water in the reservoir T_w were kept constant and the isothermal lines were constructed by repeatedly measuring the temperatures at various points in the cylinder by means of a slender alcohol thermometer of 3.3 mm diameter. As a matter of fact the room temperature could not be kept constant; it varied within a range of two or three degrees centigrade. The effect of this variation upon T_a was determined experimentally and corrections were made to the observed value of the isothermals so that the room temperature could be always considered constant at $-23°C$ in this series of experiments. Measurements were made with four different values of T_w, viz., $+5°C$, $+10°C$, $+15°C$ and $+20°C$. The isothermals with T_w at $+5°C$ are shown in Fig. 5. In that Figure one may clearly see that the warm air containing excessive water vapour goes up through the inner cylinder and is cooled gradually as it ascends from the outlet. The rate of effusion is smaller than in other cases when T_w is higher, which will be clearly seen from the more gentle gradient of the temperature distribution in this case. The accumulation of warm air in the upper part of the apparatus is shown by the existence of a high temperature region H, which is always observable at any temperature of the water. The isothermals with T_w at $+15°C$ and $+20°C$ are shown in Figs. 6 and 7 respectively. When T_w is $+15°C$ the isothermals trend similarly to the case when T_w is $+5°C$. Raising the temperature of water to $+20°C$ (Fig. 7), the accumulation of warm air in the upper part of the apparatus becomes more conspicuous and there appears a low temperature region just below the high temperature one, as shown by L in the Figure. This phenomenon will be explained by assuming that under this condition the convection of air becomes so violent

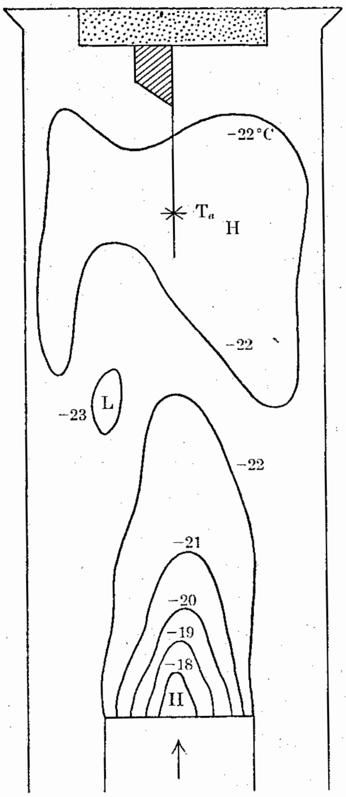


Fig. 5.
$T_r = -23°C$, $T_w = +5°C$.

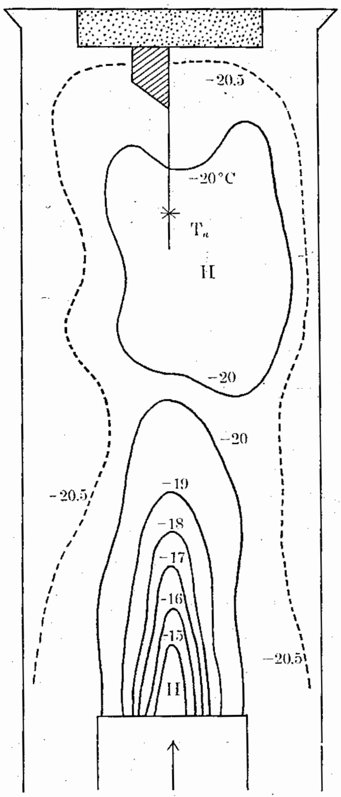


Fig. 6.
$T_r = -23°C$, $T_w = +15°C$.

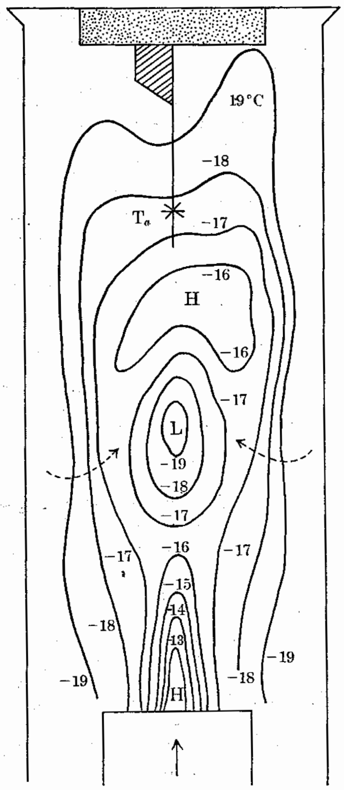


Fig. 7.
$T_r = -23°C$, $T_w = +20°C$.

that some eddies occur in this part of the apparatus. The eddies are shown roughly by the broken-line arrows in Fig. 7.

From the isothermal lines represented in Figs. 5–7 one will see that the temperature of the air where the crystal is made, T_a, is an increasing function of T_w when T_r is kept constant. The relation between T_a and T_w is shown graphically in Fig. 8, T_r being constant at $-23°C$.

It may not be needful to say that the temperature measured by a thermometer represents the mean value of

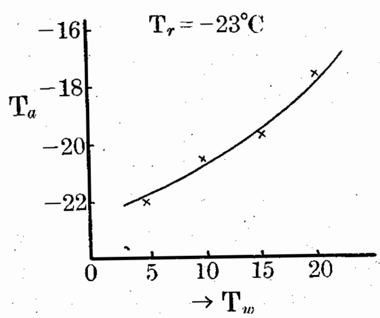


Fig. 8.

temperature at that position. The isothermals drawn in Figs. 5–7 show the mean value of temperature with respect to both space and time. The dimensions of the snow crystal to be manufactured are microscopic and accordingly the mode of its growth must be influenced strongly by the spatial fluctuation of the conditions. The fluctuation in conditions with respect to time was found by later experiments also to have some important effect upon the form of the crystal. These fluctuations are more notable when the convection of air becomes more violent; that is, when the isothermals run more closely together. This point will be discussed in the next communication, report No. 12.

4. The formation of germ of snow crystal on the filament.

In this and following papers the authors will use the term "germ" for describing the very early stage of the snow crystal. In the foregoing papers the term "nucleus" was used for this purpose, but the word nucleus would better be reserved for designating the nucleus in the original sense. The "nucleus" of snow may be an ion or a dust particle or an aerosol particle, on which water vapour condenses by sublimation. Thus a "germ" is formed. This germ is so small that its form is not yet distinguished microscopically under a usual magnification. If a germ is exposed in atmosphere supersaturated with water vapour, it grows into an "early stage of crystal", the form of the latter being observable under a microscope. A snow crystal proper is obtained by the subsequent condensation of water vapour on this early stage. As described in the previous report, it is fairly difficult to make a few isolated germs of snow crystals attach themselves to the filament. The best condition for getting the isolated germs was sought by changing the conditions of the experiments in various manners.

a) Dryness of the filament. Filaments must, regardless of the kind of material, be thoroughly dried before setting in the apparatus. In these experiments they were kept in a desiccator containing phosphorous pentaoxide for a few days before using.

b) Initial temperature of the filament. It was found to be better to set a warm filament in the apparatus. To begin the experiment the desiccator containing the filament was kept in a room at ordinary temperature; from the inner wall of the apparatus in the cold chamber the frost crystals were cleaned because they would prevent the free convection of air inside the apparatus; just before the beginning of the experiment the desiccator was brought into the cold chamber and the filament was quickly set in the apparatus and then water was poured into the reservoir.

c) Mode of increasing T_w. After setting the filament in the apparatus the increasing of T_w was carried out in three different ways, that is, (1) T_w was initially set at nearly $+8°C$ and then was raised very slowly, (2) T_w was warmed up slowly from $0°C$ and (3) T_w was raised quite rapidly. No essential difference was observed in the results obtained by the two former procedures. Isolated germs were obtained in both cases, other factors having been favourable. Photo. 4, Pl. I, shows germs obtained on a rabbit hair by increasing T_w from $+7°C$ very slowly. The upper small crystal is in the germ stage while the lower large one is in the next stage when the snow crystal begins to develop from the germ. In this case it is usually observed that one or two germs are obtained within one centimetre of the filament. Accelerating the rate of increase of T_w, more germs appear on the filament, in one centimetre of which six or seven germs are usually obtained. When T_w is increased very rapidly, the filament is always covered with numerous germs. One example is shown in Photo. 2, Pl. I. In that case T_w was raised from $+3°C$ to $+30°C$ in ten minutes. If ice crystals were made to develop from these germs, the filament would be covered with frost crystals and no artificial snow crystals could be obtained. If T_w is raised more rapidly; for example, increased from $+6°C$ to $+46°C$ in ten minutes, the germs assume the form of frozen droplets, showing that water vapour is once condensed into water droplets and then frozen. Such frozen droplets are shown in Photo. 18*a*, Pl. III. In this case T_r was $-25°C$ and the highest value of T_a was $-10°C$. The reason why the germ passed through a liquid phase momentarily is explicable as due to the excessive latent heat liberated in the process of the rapid condensation of the warm vapour. In the light of the results of the experiments described above the writers chose the process for executing the experiments as follows: after setting the filament, the temperature of water T_w, which was initially between $0°C$ and $+7°C$, is raised very slowly; waiting till a few germs appear on the filament, T_w is then raised rather quickly to the desired value corresponding to the type of crystal to be produced.

d) Nature of the filament material. As the suspension filament, rabbit hair, silk, cotton, wool and cobweb were tried. Among them rabbit hair and silk filament were found to be most suitable for the present purpose. With other filaments, the generally observed tendency was for many germs to attach themselves on the filament, although it is not impossible to get an isolated germ upon rare occasions. The structure of a rabbit hair was examined under high magnification and it was found that a few knobs occur at a moderate separation. The sketch of some of the knobs is shown in Fig. 9. After a hair had been exposed to the moist air in the cold chamber for a short time, a knob was examined under the same magnification and it was found that an ice crystal of granular form had grown on the filament, having the knob as the nucleus. In case of the condensation of water vapour into a droplet, it is well known that a nucleus must be present for the formation of the droplet. The surface tension of water accelerates the rate of evaporation and this effect is intensified rapidly as the droplet becomes smaller so that inversely a water droplet can grow larger under a given state of supersaturation only when it has got past a critical size. Besides the question of ions as condensation nuclei, fine dust particles serve as nuclei for producing droplets larger than those having the critical value. A similar phenomenon may well be expected also in case of sublimatic condensation of vapour into a crystal. In this case the surface energy of the ice crystal will play the rôle of the surface tension in the case of a liquid. If an ice crystal that grew on a knob of the filament develops to a certain dimension, the greater part of the vapour afterwards conveyed from the reservoir will condense on to this crystal, the other part of the filament being kept free from ice crystals. Later on, it was found that a silk filament which had previously been exposed to the vapour of boiling paraffin for a short time was suitable for getting isolated germs. This sort of filament was often used with apparatus No. 4. The silk filament was convenient to handle under the microscope as it is very flexible.

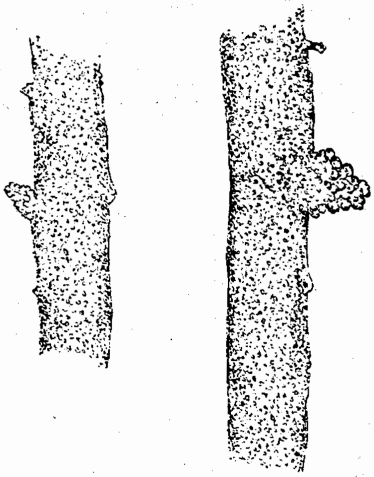


Fig. 9.

e) Thickness of the filament. Among various filaments of the same material the thinner ones were found to be more suitable for the present purpose than the thick ones. The time taken for getting a germ of moderate size after setting the filament in the apparatus was shorter for the thin ones. One example in case of a rabbit hair showed that the time

Table I.

No.	Ceiling	Filament	Initial T_w	Rate of increasing T_w	Time for germ formation	When germ is formed		Final state		T_r	Condition of germs	Final state of snow crystals
						T_a	T_w	T_a	T_w			
1	Cork	thin r.h. thick r.h.	+7°C	slow	35 m 55	−20°C	+13°C	−16°C	+13°C	−25°C	two isolated germs	beautiful fern-like crystals
2	Cork	thin r.h.	+8°C	fairly rapid	20 m	−15°C	+13°C	−12°C	+19°C	−22°C	many germs	assemblage of sector form
3	Cork	”	0	very slow	25	−22	+ 7	−17	+10	−23	two germs	assemblage of sector form
4	Cork	”	+7	very rapid	15	−15	+30	−18	+10	−25	innumerable	aggregate of irregular sectors
5	Wood	”	+8°C	slow	1 h 5 m	−18°C	+12°C	−16°C	+14°C	−24°C	one or two	beautiful fern-like, broad branch
6	Wood	”	−5	slow	2 5	−18	+ 9	−15	+18	−23	one or two	fern-like crystals
7	Wood	”	+7	very rapid	40	−14	+45	−16	+14	−25	frozen droplets	aggregate of irregular frosts
8	Copper	”	+5°C	slow	1 h 40 m	−20°C	+10°C	−22°C	+14°C	−24°C	a few germs	spatial dendritic, assemblage of sectors
9	Copper	”	0	slow	1 30	−22	+12	−23	+15	−24	two germs	fern-like crystals

was 35 min for the thin and 55 min for the thick one, T_a being at $-20°C$ and T_w at $+13°C$.

f) The effect of the ceiling. The ceiling of the apparatus, D in Fig. 1, has some influence upon the process of the formation of the germ and the subsequent growth of crystal. T_a is much influenced by the material of the ceiling. Cork, wood and copper were tried. With a cork ceiling T_a is highest for given values of T_w and T_r. When it was used isolated germs were easily formed and the time taken for their formation was shortest, being 20 min and 35 min for two examples respectively. In promoting the subsequent growth of the snow crystal the cork ceiling is not always favourable, as T_a sometimes becomes too high for many sorts of crystals except a fern-like one, for the production of which type the cork ceiling is the most suitable. With a copper ceiling T_a is lowest and the time taken in the formation of nuclei is longest, lying between one hour and two hours. In case of a wooden ceiling the state of things stands between the two extremities.

The conditions for the formation of germs on the filament and the subsequent growth of artificial snow crystals have been tabulated in Table I for nine examples. The considerations stated in a)–f) will be understood from the data in the Table.

5. The early stage of artificial snow crystals.

As described in the foregoing section, the hair is set in the apparatus and the water temperature is raised gradually; after waiting half an hour or so a germ of snow is seen to attach itself on the filament. At first the form of this germ is not clearly seen but before long it develops into a defined form observable under a microscope with the usual magnification. This stage will be called the early stage of snow crystal. The form of the crystal at this stage is not simple. Almost all types of snow crystals are seen among the copious variety of artificial crystals in their early stages, and moreover some rare types were found which are not often to be seen in natural snow. Twelve types of them are shown schematically in Fig. 10. The explanation of the form and the conditions under which the crystals are produced are summarized in Table II.

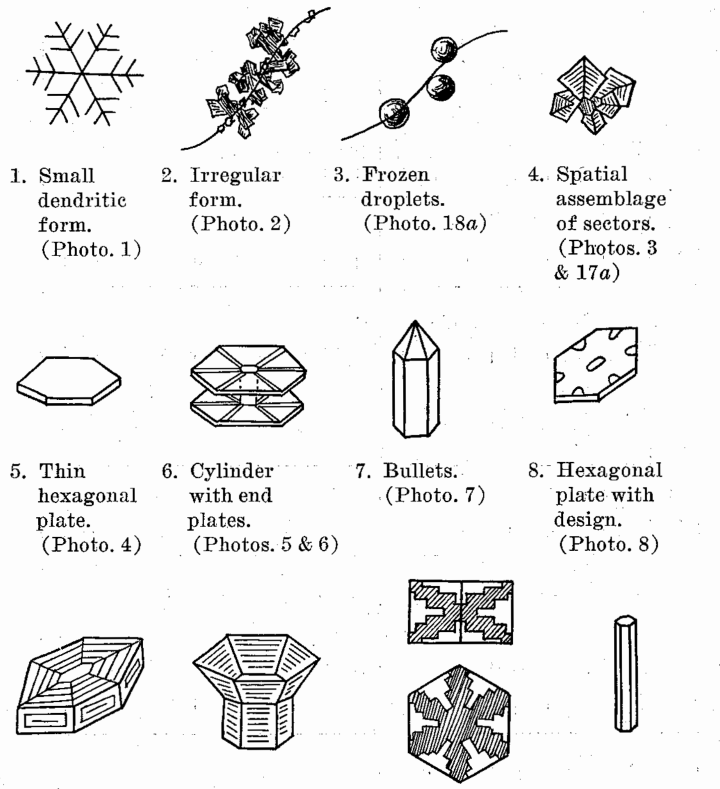
Table II.

Type No.	Photo. No.	Explanation of the form	App. No.	T_r	T_w initial	T_w middle	T_w last	T_a initial	T_a middle	T_a last	t
1	1	Small dendritic plane form	0	−30°C	+5°C	+10°C	+15°C	−19°C	−17°C	−18°C	30 min.
2	2	Irregular form	1	−26	+3	+35	+20	−20	−13	−15	30 "
3	18*a*	Frozen droplets	1	−25	+6	+46	+25	−22	−10	−12	30 "
4	3	Spatial assemblage of sectors	1	−23	+10	+16	+19	−15	−13	−12	1.5 h
"	17*a*	" " " "	1	−26	+8	+7	+6	−15	−17	−20	2 "
5	4	Thin hexagonal plate	1	−24	+6	+10	+12	−24	−22	−16	2 "
6	5	Cylinder with end plates	1	−25	0	+8	+20	−20	−20	−14	5.5 h
"	6	" " " "	0	−25	+6	+10	+13	−18	−19	−17	6 "
7	7	Bullets	4	−30	+3	+5	+10	−29	−27	−25	7 "
8	8	Hexagonal plate with design	4	−30	+4	+4.5	+4.5	−26	−27	−28	15 "
9	9	Thick hexagonal plate	4	−40	+2	+4	+1	−38	−36	−39	18 "
"	19*a*	" " "	0	—	+18	+11	+11	−18	−21	−18	16 "
10	20*a*	Cup crystal	1	−25	+5	+4.5	+4	−21	−21	−19	17 "
11	10	Skeleton form of prism	4	−24	+6	+8	+10	−22	−22	−20	20 "
"	11	" " " "	4	−24	+6	+8	+10	−22	−22	−20	20 "
12	12	Solid needle without structure	4(S)	−32	+4	+4	+4	−30	−30	−28	25 "

t: time taken for the development of crystal to the stage shown in the photograph, measured from the moment the hair was exposed to the supersaturated atmosphere.

No. 0: the old apparatus used in the experiment described in report No. 10.

4(S): apparatus No. 4 with a stop diaphragm for the circulation of air current.



1. Small dendritic form. (Photo. 1)
2. Irregular form. (Photo. 2)
3. Frozen droplets. (Photo. 18a)
4. Spatial assemblage of sectors. (Photos. 3 & 17a)
5. Thin hexagonal plate. (Photo. 4)
6. Cylinder with end plates. (Photos. 5 & 6)
7. Bullets. (Photo. 7)
8. Hexagonal plate with design. (Photo. 8)
9. Thick hexagonal plate. (Photos. 9 & 19a)
10. Cup crystal. (Photo. 20a)
11. Skeleton form of prism. (Photos. 10 & 11)
12. Solid needle. (Photo. 12)

Fig. 10.

The twelve types of these early stages can be roughly classified into three groups.

I) Those crystals which are rather quickly formed. Small dendritic plane form (No. 1 in Fig. 10), irregular form (No. 2) and frozen droplets (No. 3) are formed rather quickly. As a usual thing they develop to the stages shown in the photographs within half an hour. It was often observed that under just similar conditions the crystal sometimes develops into a dendritic form and in other cases grows into a spatial assemblage of sectors. In the former case the crystal develops quickly and in the latter slowly. The difference may be caused by the difference in the form of the germ, which itself cannot be observed microscopically under usual magnification.

II) Those crystals which are formed by an intermediate process. Spatial assemblage of sectors (No. 4) and thin hexagonal plate (No. 5) are usually formed within two hours. The small hexagonal plate seen in Photo. 4, Plate I, is the crystal of type No. 5 and the larger flake in the same photograph seems to be a crystal developed from a thin plate similar to the one above mentioned. The subsequent growth of the snow crystal is influenced by the form of the crystal in its early stage. This point will be discussed in detail in article 7.

III) Those crystals which are slowly formed. Cylinder with end plates (No. 6), bullets (No. 7), thick hexagonal plate (Nos. 8 and 9), cup crystal (No. 10) skeleton form of prism (No. 11) and solid needle (No. 12) belong to this group. It takes more than five hours for the development to the stages shown in the photographs. t in Table II shows the time interval between the moment of setting the hair in the apparatus and that of taking the photograph. Most of the values of t exceed 15 hours, but this value has no essential importance, because in much less time the crystal develops into a similar form being only slightly smaller in size than that shown in the photograph. For example, t for the skeleton form of pirsm is noted as 20 hours, but in 10 hours, say, after the beginning of the experiment the crystal takes a similar form to that shown in the photograph and after that time the growth of the crystal is very slow.

Nos. 8, 9, 10 and 11 in Fig. 10 belong to the same class. They are all modifications of the skeleton form of hexagonal prism shown in No. 11 (Photos. 10 and 11, Plate I), in which the shaded parts represent the space filled up with ice material. The design in the hexagonal plate (No. 8) is due to the cavities, which correspond to the stepped hollows in case of the thick plate (No. 9). These stepped hollows develop to their full extent in No. 11, causing the crystal to assume a typical skeleton form. When the parts filled with ice material become very thin the crystal grows in the form of a cup (No. 10).

The cylinder with end plates is usually composed of a hexagonal cylinder with two plates attached one to each end, but sometimes a curious form is obtained in case of artificial snow. One example is shown in Photo. 6, Plate I, where the cylinder is a solid needle of ice without marked structure. This sort of needle can be obtained by itself as shown in Photo. 12. It is formed at a lower temperature with a small rate of supply of water vapour. Further explanation will be given in article 10.

6. The experimental procedure in making artificial snow.

The procedure in making artificial snow is as follows. The apparatus is set in the cold chamber and left till it cools down nearly to the temperature of the room. Then a few rabbit hair or silk filaments, which have previously been thoroughly dried up, are set in the apparatus and at the same time some water is poured into the reservoir. The temperature of the water T_w is raised slowly. One must wait till a few germs appear on the filament, then T_w is adjusted to the required value corresponding to the form of crystal to be manufactured. Three values of temperature T_r, T_a, T_w are recorded from time to time. They are plotted in a graph as the function of time and this graph is taken to represent the history of the development of a snow crystal. Four examples of these graphs are shown in Figs. 11*a–d*.

Fig. 11*a* shows the course of the process by which a fern-like plane crystal is formed. A photograph of such a crystal is reproduced in Photo. 13, Pl. II. When the rabbit hair is set in the apparatus, T_w stood at $+8°$C. It was raised gradually to $+10°$C within about one hour, and a crystal germ was observed on the hair. Then the heating current was increased so that T_w was raised to $+15°$C in 35 min. T_r was kept at nearly $-30°$C till the appearance of the germ, after that it went up to $-27°$C. The temperature of the cold chamber often varied within the range of a few degrees, which could not be avoided, because several other experiments were carried on in parallel in this chamber. T_a was always few degrees higher than T_r and the difference increased with T_w. One example of the relation between T_a and T_w when T_r was constant has already been given in Fig. 8, in which case only the equilibrium state was dealt with. When T_w was changing, there was some time lag in the increase of T_a. The example graphed in Fig. 11*a* shows that a fern-like plane crystal grows very rapidly, compared with the other sorts of snow. In this case the rate of growth amounted to 11 mm/hour. In the persent paper the rate of growth of a crystal means the increase of the dimension in one hour, the latter being taken to be the diameter of a circle or a sphere enclosing the crystal.*

Fig. 11*b* shows the course of the formation of a plane dendritic crystal of broad branch type (Photo. 14, Plate II). The condition for the formation of germs is similar to the former case. After the germs were

* The rate of growth thus defined is in amount twice the rate of growth of one branch, which latter definition was adopted in the foregoing paper No. 10.

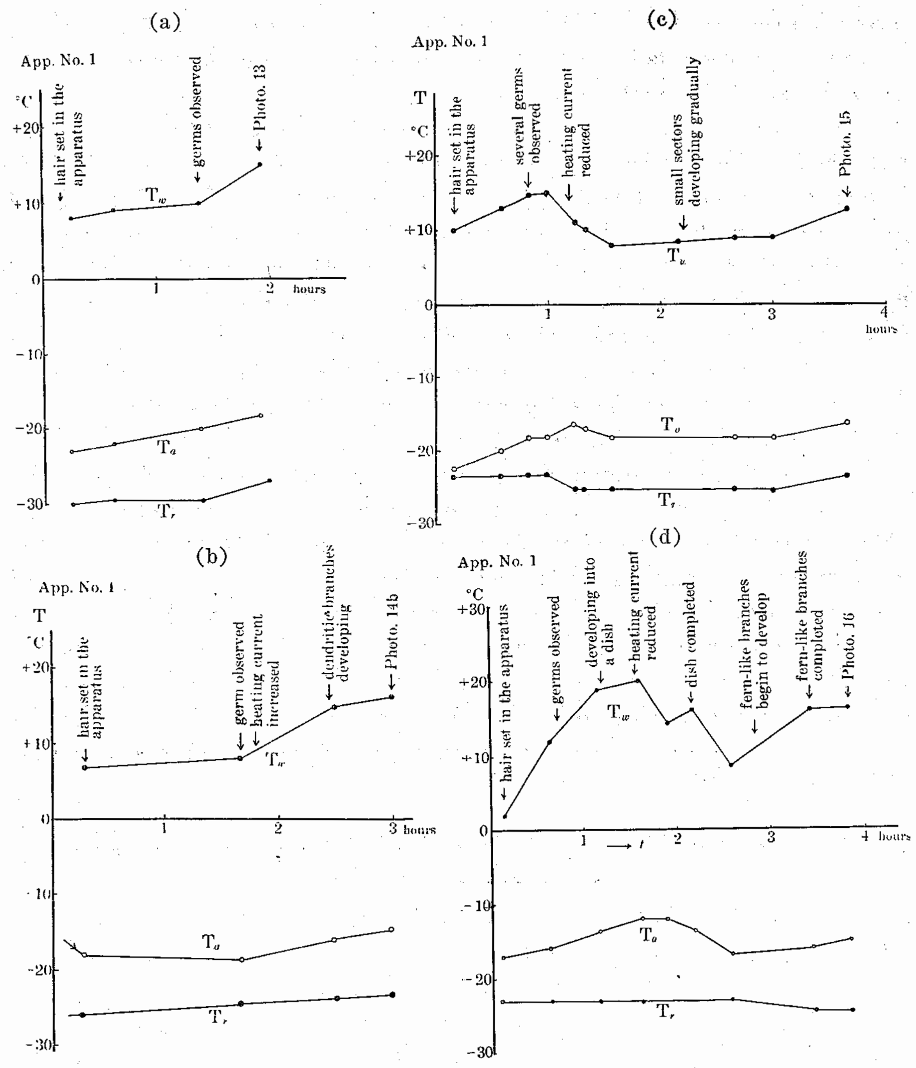


Fig. 11.

observed on the filament, T_w was raised from $+8°C$ to $+16°C$ in 80 min. The mean rate of growth was about 1.2 min/hour in this case.

Fig. 11*c* shows the course of the formation of a crystal of a spatial assemblage of sectors. In this case T_w was increased at a faster rate than in the previous two cases and consequently, as described in section 4*c*), several germs formed on the filament. Then T_w was reduced to nearly $+9°C$ and kept there for two hours. The snow thus manufactured developed into a spatial assemblage of sectors as shown in Photo. 15, Pl. II. The rate of growth is less in this case than that for the dendritic crystals, being an average 0.6 mm/hour.

In Fig. 11*d* a more complicated process is graphed. After the appearance of the germs, T_w was raised still higher. The snow began to develop into a type of cup crystal, or better to say, a shallow hexagonal dish. Then the heating current was reduced so that T_w and consequently T_a were lowered to the state suitable for the formation of dendritic branches. After that T_w was increased in a similar manner to the case of *a* or *b*. Dendritic branches began to develop, as expected, from the edges of the dish. The crystal thus formed is shown in Photo. 16, Pl. II. The rate of growth is about 4 mm/hour for the dendritic appendices. In the four experiments above cited apparatus No. 1 was used throughout.

It is generally accepted and it is true that the form of snow is determined chiefly by the degree of supersaturation of the surrounding atmosphere during the course of its formation. From the physical view point the degree of supersaturation is one of the most important factors governing the rate of growth of a crystal. This rate of growth in turn is itself one of the factors controlling the variation of crystal form. Besides the degree of supersaturation there are other factors controlling the rate of growth. It is, therefore, better to take the rate of growth directly, rather than the degree of supersaturation, as the parameter for describing the variation of crystal form.

7. The form of crystal in the early stage and its influence upon the subsequent growth.

It can reasonably be expected that the form of snow is strongly influenced by the form of the crystal in its early stage. The results of investigations on this point are described in this section.

In natural snow three sorts of dendritic crystals are observed with similar frequency in our climate. They are the ordinary plane dendritic one, the spatial assemblage of dendritic branches with a stellar base and the spatial assemblage of radiating type. It is quite natural to consider that the first one develops from a small dendritic crystal as shown in Photo. 1 when the subsequent conditions are favourable for the dendritic growth. The second one is probably produced by the attachment of other nuclei to the various points of the branches of the first one, as described before. The third one, the radiating type, has two sorts, the one having a stone at the central region and the other lacking such a stone. The stone observable in the former sort consists of an assemblage of prisms, as has been described in detail in report No. 7. The latter type was found by the present experiment to have been developed from a spatial assemblage of sectors. One example of the course of formation of this type is graphed in Fig. 12. T_w was kept rather low in this case and germs were obtained two hours after the beginning of the experiment. The early stage of crystal developed from this germ took the form of a spatial assemblage of sectors as reproduced in Photo. 17*a*, Pl. II. After taking the photograph the hair was again set in the apparatus and the experiment was continued by increasing T_w rapidly so that dendritic extensions were expected. After one hour the crystals developed into a spatial assemblage of radiating type as shown in Photo. 17*b*. The crystal developed from the germ reproduced in Photo. 17*a* is the upper one in Photo. 17*b*.

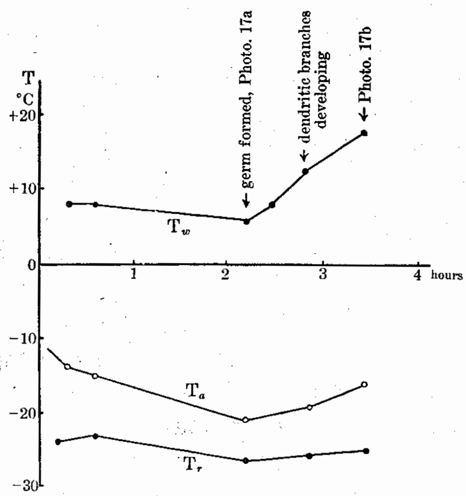


Fig. 12.

Fig. 13 and Photos. 18*a*, *b*, Pl. III, show irregular crystals developed from frozen droplets. In this case T_w was suddenly raised by pouring hot water into the reservoir. Many frozen droplets were obtained on the filament. The crystals developed from these frozen droplets assumed the form of irregular assemblages of sectors as shown in Photo. 18*b*. Some irregular particles observed in natural snow may have been produced by developing from frozen droplets; such a phenomenon is likely met with when a marked temperature inversion

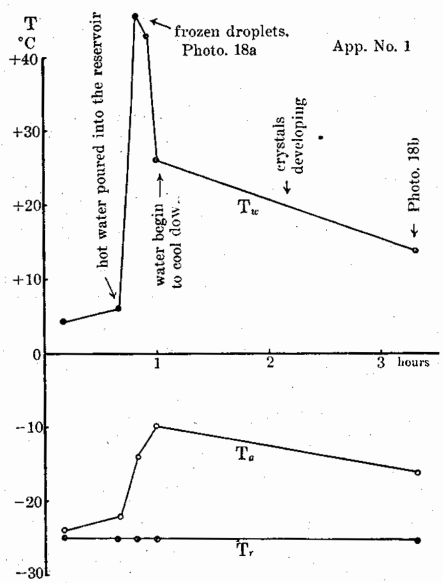


Fig. 13.

takes place in the atmosphere.

As an example of the crystal made by a slow process, thick hexagonal plates are shown in Photo. 19*a*, Pl. III. The crystal of apparently cylindrical form that is seen in Photo. 19*a* next to the hexagonal plate is the side view of a similar plate. They were obtained in the old apparatus used in report No. 10, by keeping T_w between $+18°C$ and $+11°C$ for 16 hours as tabulated above in Table II. Then T_w was raised to nearly $+30°C$. Plane branches began to extend out from the edges of the plate and after two hours the crystal developed into the state shown in Photo. 19*b*. The side view shows that two plane crystals attach themselves to each face of the plate. Additional good examples of the column with two plane crystals attached to each end are described in article 11.

Photo. 20*a*, Pl. III, is an example of a cup crystal. This was made in apparatus No. 1 by a slow process. T_w was kept at nearly $+5°C$ and left for 17 hours. After taking Photo. 20*a*, the hair was reset in the apparatus and T_w was gradually raised to $+21°C$ within two hours. Broad plane branches extended from the edges of the hexagonal cup and the crystal developed into the form shown in Photo. 20*b*.

From the examples above described one may clearly see the influence of the form of the early stage upon the subsequent growth of a crystal.

8. Convection of air and form of crystal.

In the discussions in the foregoing papers, the degree of supersaturation was represented by the supersaturation ratio s, which was defined as the ratio of the saturation vapour pressure of water at T_w to that at T_a, and the relation between s and the crystal form was studied. This s can be taken as a measure for determining the rate of supply of water vapour, but it will not represent strictly the degree of supersaturation at the spot where the crystal is made, because the entire amount of water vapour evaporated from the reservoir is not conveyed to the place of crystal formation. Some portion of the vapour will condense as frost crystals on the inside of the wall. The form of the upper part of the apparatus will modify the manner of convection and consequently modify the rate of supply of water vapour to the crystal being produced. Experiments were carried out for the purpose of clarifying these points.

a) Effect of frost crystals adhering to the inside of the wall. If a single apparatus is used continually for a few series of experiments, the lower part of the inside of the glass wall becomes covered with frost crystals. It was found that these frost crystals growing in clusters prevent, to a considerable extent, the free circulation of an upward air current. For getting a certain type of crystal it was necessary to increase T_w much higher than the usual value of the same when no frost was observed on the wall.

The crystal of sector form shown in Photo. 21, Pl. IV, is a good example. In this case many frost crystals grew in clusters on the inside of the wall. The crystal took six hours for developing to the state shown in the photograph, T_w having been kept between $+32°C$ and $+36°C$, which is extraordinarily high. The mean rate of growth of crystal amounted only to 0.3 mm/hour. The hexagonal form seen in the central part of this crystal is a cup crystal, taking the form of a shallow hexagonal dish. Photo. 22, Pl. IV, is shown for comparison. This dendritic plane crystal was produced in apparatus No. 1, which had previously been thoroughly cleaned from frost crystals. It took only one hour to obtain this form, T_w being kept at nearly $+7°C$. The rate of growth was 3.5 mm/hour.

From these examples shown in Photos. 21 and 22 and the descriptions, one will clearly understand the influence of frost crystals in preventing the convection of water vapour. In the later experiments, therefore, the frost crystals adhering to the inside of wall were entirely removed each time just before a series of experiments was started.

b) Form of the space where the crystal is made.

The form of the upper part of the apparatus where the artificial snow is made has a considerable influence upon the form of the crystal produced. In case of apparatus No. 2, which is similar in construction to No. 1 but shorter, T_a is higher than that in apparatus No. 1 for the same T_r and T_w, because much nearer the H at the air outlet (cf. Figs. 1 & 2). This effect will be clearly understood from the distribution of the isothermal lines of T_a, which were measured in apparatus No. 1 and shown in Figs. 5–7.

In case of apparatus No. 3 the convection of water vapour in the top portion seems to be weakened, as this part was made slender as shown in Fig. 3. In order to attain the same rate of supply of water vapour in the case of N.o 3 as that in No. 1, T_w must be heightened. The crystal shown in Photo. 23, Pl. IV, was made in apparatus No. 3. The course of the formation is shown by solid lines in Fig. 14. After the appearance of the germ, T_w was raised from $+6°C$ to $+18°C$ within about two hours. With this value of T_w, the crystal would be developed into a dendritic form if apparatus No. 1 were used. In the present case, however, the crystal grew into a hexagonal plate with extensions of broad branches.

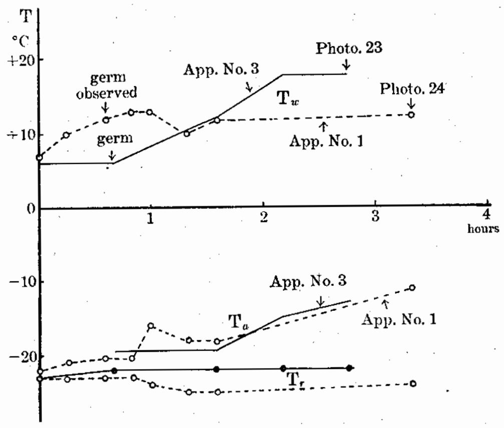


Fig. 14.

The mean rate of growth was 0.9 mm/hour. Photo. 24 is shown for comparison. In this case apparatus No. 1 was used and the crystal developed into a beautiful fern-like type. The course of the formation is shown by dotted lines in Fig. 14. T_r and T_a were more or less the same as the former case, and T_w was kept at nearly $+12°C$ after the formation of the germ, which is decidedly lower than in the case of the crystal in Photo. 23. The rate of growth was about 3.5 mm/hour. The fern-like form of the crystal, Photo. 24, indicates that the supply of water vapour was, in spite of the lower value of T_w, larger in amount than that of the preceding case, Photo. 23.

This effect must be assigned to the form of the apparatus where the crystals are made, which hinders or facilitates the convection of water vapour. In later discussion, therefore, the results obtained with the same apparatus must be studied as one group and those with the other apparatus as another group.

c) Non-homogeneity of convection current.

The non-homogeneity of the convection current will be seen from the isothermals shown in Figs. 5–7. When several filaments are set at different positions in an apparatus, the crystals attached to the different filaments are usually not the same in form. It is quite natural that this sort of non-homogeneity should take place in the apparatus.

During the course of the experiments it was found that the non-homogeneity of the convection current can occur also on a microscopic scale, which is seen from the form of some peculiar crystals. Two examples of such are reproduced in Photos. 25 and 26, Pl. IV. The crystal shown in Photo. 25 is composed of dendritic branches on one side and sectors on the other. This crystal was made in apparatus No. 3 under the conditions that T_a was nearly $-22°C$ and T_w increasing from $+5°C$ to $+12°C$ within 3 hours. The other example, Photo. 26, is composed of dendritic branches and a half portion of a hexagonal plate. This crystal was made in apparatus No. 4 with T_a at $-16°C$ and T_w gradually increasing from

+11°C to +13°C within 4 hours. In nature this sort of crystal is not formed because of the rotation of the crystal while it is falling.

d) Effect of introducing a stop diaphragm upon the convection of water vapour.

In order to clarify the effect of the rate of the supply of water vapour to the spot where the crystal is made, stop diaphragms of various apertures were introduced in apparatus No. 1. The diaphragm was made of a brass plate having a circular hole of variable diameters. It was placed on the top of the inner glass cylinder, at 0 in Fig. 1. Experiments were carried out with four sorts of diaphragms, the diameter of the circular apertures being 3 cm, 2 cm, 1 cm and 0.6 cm respectively. The results are summarized in Table III. T_w or T_a in the column noted "subsequent growth" shows the mean value of T_w or T_a during the course of the growth of the crystal subsequent to the germ formation.

From the data in the Table one will see that the smaller the diameter of the aperture, the longer the time for the germ formation becomes. Additional interesting phenomena were observed in the subsequent growth of the crystal following the formation of the germ. When the stop diaphragm was used, T_w was, as expected, much higher than when the diaphragm was not used, for getting a similar type of crystal.

Table III.

Diameter of aperture	Time for germ formation	T_r	When germ is formed		During subsequent growth		Time needed for subsequent growth	Form of crystal produced
			T_w	T_a	T_w	T_a		
3 cm	1 h	−26°C	+ 6°C	−22°C	+ 8°C	−21°C	3 h	spatial dendritic with droplets
2 cm	30 min	−26	+12	−22	+10	−20	3 h	spatial dendritic with droplets
1 cm	1 h	−27	+16	−24	+30	−22	5 h	spatial dendritic with droplets
„	3 h	−26	+14	−22	+21	−20	2.5 h	spatial assemblage of plates
„	22 h	−25	+18	−23	+13	−23	20 h	irregular assemblage of small plates
0.6 cm	1.5 h	−26	+21	−23	+25	−22	3.5 h	plane dendritic with droplets (Photo. 27)
„	24 h	−25	+18	−24	+20	−24	17 h	irregular assemblage of small plates (Photo. 28)

When the aperture is 1 cm in diameter, T_w must be raised to $+30°C$ in order to get a dendritic crystal. It was found that dendritic crystals thus produced had many water droplets attached. These droplets may be explained as fog particles, which condensed from the supersaturated air current when the latter was cooled down by passing the cold diaphragm. This sort of crystal, the spatial assemblage of dendritic branches with droplets, was obtained with T_w at $+10°C$ when the aperture was 2 cm in diameter, though it had to be as high as $+30°C$ when the latter was 1 cm. With the aperture 3 cm in diameter, the corresponding value of T_w was $+8°C$.

Upon decreasing T_w to $+21°C$ when the aperture was 1 cm, the crystal became a spatial assemblage of plates. If T_w was still further reduced, to $+13°C$, an irregular assemblage of small plates was obtained. A similar effect was observed in the case when the aperture was 0.6 cm. Two examples are shown in Photos. 27 and 28, Pl. V. Photo. 27 is a plane dendritic crystal with water droplets and Photo. 28 an irregular assemblage of small plates. The former was obtained with T_w at $+25°C$ and T_a at $-22°C$, and the latter with T_w at $+20°C$ and T_a at $-24°C$.

It will be clearly seen from the results of the experiments above described that the increase of the aperture of the diaphragm has a similar effect to the increase in T_w.

9. The results of experiments carried out with the room temperature between −20°C and −30°C.

The details of the experimental procedure and technical precautions to be taken in these experiments on artificial snow have been described in full detail in the foregoing sections. The results of the experiments carried out are tabulated in Tables IV–VIII. In this series of the experiments the temperature of the room was kept between $-20°C$ and $-30°C$. The experiments carried out at a lower room temperature will be described separately in the next section.

As stated in the foregoing article 8, the supersaturation ratio s which has been considered in former reports as determining the conditions of the formation of the crystal, has less physical meaning than the absolute value of the rate of growth of the crystal. In paying special attention to the latter, the forms of the crystal were classified into five groups in Tables IV–VIII: in IV, fern-like crystal; in V, ordinary dendritic type and broad branches; in VI, sectors and plates; in VII, irregular form and side planes, and in VIII, miscellaneous. In these Tables, "Photo. No." means the

Table IV. Fern-like crystal.

Apparatus number	No.	Photo. No.	Experiment number	Form of crystal	T_r	T_a			T_w			t	Rate of growth mm/hour
					mean	initial	middle	final	initial	middle	final		
No. 1	1	22	T 61–64	six-petalled flower	−22°C	−16°C	−17°C	−18°C	+ 8°C	+ 7°C	+ 6°C	1 h	3.5
	2		T 21–22	spatial, radiating	−23	−13	−14	−16	+17	+17	+15	1.5 h	(2.3)
	3	16	T 52–57	beautiful fern-like	−23	−17	−16	−15	+ 8	+12	+15	1 h	4.5
	4		T 81–82	with water droplets	−23	−18	−16	−15	+10	+14	+16	2 h	—
	5		T 18–19	six-petalled flower	−24	−17	−16	−15	+ 5	+13	+20	1 h	3.6
	6		T 45–47	with few droplets	−24	−17	−17	−17	+ 5	+ 7	+20	1.5 h	(2.7)
	7		T 68–71	ordinary fern-like	−24	−23	−22	−22	+ 4	+ 6	+14	1.5 h	3.5
	8		T 35–41	with water droplets	−25	−18	−17	−15	+ 5	+10	+15	2 h	(2.0)
	9	24	T 94–96	beautiful fern-like	−25	−16	−15	−12	+10	+12	+13	2 h	3.5
	10		T 146	plane, beautiful	−26	−21	−19	−16	+ 6	+13	+19	1 h	5.5
	11	17b	T 142–144	spatial, radiating	−26	−21	−19	−16	+ 6	+13	+19	1 h	(3.0)
	12	13	T 218–221	beautiful fern-like	−28	−20	−19	−18	+10	+13	+15	30 m	10.0
No. 3	13		T 183–185	with water droplets	−24	−23	−20	−23	+10	+17	+19	2 h	(2.0)
	14		T 120–121	ordinary fern-like	−25	−22	−21	−21	+15	+15	+15	1 h	2.9
No. 4	15		M 20–22	beautiful fern-like	−23	−17	−17	−18	+10	+25	+30	2 h	4.5
	16		M 364	beautiful fern-like	−23	−16	−16	−16	+12	+12	+13	1 h	5.5
	17		M 59–62	ordinary fern-like	−23	−18	−17	−19	+13	+20	+20	40 m	4.5
	18		M 13–16	beautiful fern-like	−24	−19	−17	−17	+13	+25	+30	50 m	3.5
	19		M 273	beautiful fern-like	−24	−17	−16	−16	+12	+13	+14	40 m	5.0
	20		M 353–356	ordinary fern-like	−26	−16	−16	−17	+11	+14	+16	30 m	4.0

mean 4.6 mm/hour

number of photographs reproduced in the Plates of this paper and t is the time taken for the development of the crystal, measured from the moment when the subsequent growth of crystal started from the germ or from the early stage. The crystals marked with an asterisk were made in the following manner: the hair was exposed in the apparatus to an atmosphere of a comparatively low degree of supersaturation and the germ was made to attach itself on the filament by leaving the hair overnight in the apparatus; the subsequent growth of the crystal was started the next morning.

The dendritic plane crystals were classified into two kinds. The fern-like one is known to be largest in dimension in the case of natural snow and the rate of growth is found to be greatest, as will be seen by comparing the data in the Tables. In some cases the rate of growth amounted to as much as 10 mm/hour[1], but usually it was between 3 and 6 mm/hour. When water droplets attach to a crystal, the rate of growth became smaller. Sometimes the fern-like branches grew in the form of a spatial assemblage of radiating type. In this case also the rate of growth was smaller than in the case of plane dendritic type. Excluding these two cases, just mentioned, which are shown in parentheses in the last column of Table IV, the mean rate of growth of the fern-like crystal is 4.6 mm/hour.

The ordinary dendritic crystal, the broad branch type and the crystals in the intermediate form are summarized in one group and the conditions of their formation are tabulated in Table V. Examples of the ordinary dendritic crystal and the broad branch type which were made artificially, are reproduced in Photos. 14 and 29 respectively. The rate of growth is decidedly smaller in this type than in the previous case, ranging between 0.6 and 1.8 mm/hour. The mean of eight examples is 1.3 mm/hour. The broad branch type appears to be formed by a slower process than is the dendritic one, but there are not sufficient data for determining this point definitely.

In Table VI, the crystal with thin branches in sector form (Photo. 40), that with thick branches in the same form (Photo. 39), the spatial assemblage of sectors (Photo. 15), the plate and the same with simple extensions (Photo. 23) are tabulated as one group. As a usual thing the rate of growth is less than 1 mm/hour and the mean of ten cases is 0.66 mm/hour.

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1) In report No. 10 it was reported that the rate of growth was measured to be 0.045 mm/sec for one example of an artificial frost of fern-like type. This rate of growth means that of one branch of crystal; the rate of increase in dimension will be 11 mm/hour if the crystal develops freely into a form with six rays.

Table V. Ordinary dendritic and broad branches.

Apparatus number	No.	Photo. No.	Experiment number	Form of crystal	T_r	T_a			T_w			t	Rate of growth mm/hour
					mean	initial	middle	final	initial	middle	final		
No. 1	1		T 127	ordinary dend. small	−23°C	−18°C	−17°C	−15°C	+10°C	+14°C	+18°C	1 h	1.3
	2	29	T 154	broad branches	−23	−16	−16	−17	+12	+10	+ 6	2 h	0.6
	3	14	T 165	ordinary dendritic	−24	−19	−17	−15	+ 8	+13	+16	1.5 h	1.2
	4		T 76–80	broad branches	−24	−18	−17	−17	—	—	—	2 h	—
	5		T 180	*dendritic	−24	−19	−17	−14	+ 4	+15	+21	2 h	1.7
	6		T 97	ordinary dendritic	−25	−16	−15	−12	+10	+12	+13	2 h	1.7
	7		T 34	„ „	−25	−18	−17	−15	+ 5	+10	+15	2 h	0.7
	8		T 87	„ „	−25	−19	−18	−18	+10	+18	+18	2.5 h	—
	9		T 203–204	„ „	−25	−19	−17	−16	+10	+12	+15	2 h	1.8
	10		T 42–44	broad branches	−26	−17	−19	−17	+ 5	+ 5	+11	1.5 h	1.2

mean 1.3 mm/hour

* Germ of crystal was made very slowly by leaving the filament in the apparatus overnight.

Table VI. Sectors and plates.

Apparatus number	No.	Photo. No.	Experiment number	Form of crystal	T_r mean	T_a initial	T_a middle	T_a final	T_w initial	T_w middle	T_w final	t	Rate of growth mm/hour
No. 1	1		T 48–50	*assemblage of sectors and plates	−23°C	−18°C	−18°C	−18°C	+12°C	+7°C	+2°C	13 h	0.2
	2		T 72–74	assemblage of sectors	−23	−16	−15	−14	+11	+15	+19	2.5 h	—
	3	39	T 101–103	sectors, thick	−23	−15	−13	−11	+16	+19	+19	1.5 h	0.6
	4	40	T 104–107	sectors, thin	−24	−22	−20	−18	+ 7	+ 8	+ 9	2.5 h	1.1
	5		T 85–86	sectors and plates	−25	−20	−20	−18	—	—	—	1.5 h	—
	6	15	T 117–118	spatial assemblage of sectors	−25	−18	−18	−16	+ 8	+ 9	+10	2.5 h	0.6
	7		T 112–113	sectors, thin	−26	−20	−21	−21	+ 8	+10	+12	1 h	1.2
No. 2	8		T 1–2	*assemblage of plates	−23	−14	−14	−15	+10	+10	+10	6 h	—
	9	21	T 9–13	assemblage of sectors	−23	−16	−10	−15	+32	+36	+36	6 h	0.3
No. 3	10	23	T 58	plate with simple ext.	−22	−19	−15	−13	+ 6	+13	+18	2 h	0.9
	11		T 130–131	assemblage of sectors	−24	−23	−22	−22	+ 9	+12	+13	1.5 h	1.0
	12		T 83–84	spatial assemblage of plate	−25	−24	−23	−24	+15	+12	+12	2 h	—
No. 4	13		M 363	plate	−24	−16	−15	−16	+10	+11	+12	3 h	0.3
	14		M 298	*sectors	−25	−16	−18	−16	+ 8	+12	+13	4 h	0.4

mean 0.66 mm/hour

* Germ of crystal was made very slowly by leaving the filament in the apparatus overnight.

This rate is approximately one half that of the ordinary dendritic crystal. T_w was usually lower in this classification of crystals than that in the former two groups, so that the supersaturation ratio is smaller. Sometimes T_w reached an exceptionally high point as No. 9 in Table VI. In this case frost crystals adhering to the inside of the apparatus wall prevented the free circulation of supersaturated air. (cf. article 8*a*). There are two kinds of sectors, one is thick and the other is thin, as shown in Photos. 39 and 40, Pl. VII, respectively. The thin sectors grow at a faster rate than do the thick ones, as shown by Nos. 3, 4 and 7 in Table VI. The mechanism of the formation of these two kinds of sectors will be discussed in section 11*a*).

In Table VII the irregular form and side planes are tabulated as one group. One example of the crystal with side planes is reproduced in Photo. 30 and that of the irregular form in Photo. 31, Pl. V. The former is reported as a novel type of crystal in the general classification of natural snow, report No. 8, and is seldom observed in our Hokkaido climate. This type is a columnar crystal with extended side planes. The mechanism of its formation is described below in section 11*g*). The irregular form is composed of an assemblage of columns, small sectors, cups and side planes. T_w was usually low in the production of such forms and the rate of growth was comparatively small, being 0.5 mm/hour as the mean. Attention must be called to the fact that most of the cases of side planes in Table VII are marked with an asterisk; that is, they were developed from germs which were made very slowly by being left in the apparatus overnight at a low T_w. The germ or the early stage of the crystal seems to be in a favourable condition for extending "buds" of side planes when it is exposed to a less supersaturated atmosphere for a long time. T_r in this case was always lower than in the previous cases, being nearly at $-30°$C.

Data on the other sorts of crystals not included in Tables IV–VII are summarized in Table VIII. The needle crystals were produced in this series of experiments by leaving the filament in the apparatus overnight with a moderately high T_w. One example of the needle thus produced is shown in Photo. 32, Pl. V. The structure of this needle is quite similar to that of the "component pillar" of the natural needle. Comparing Photo. 32 with Photo. 30 of report No. 7, one will note the very close resemblance. Nos. 1 and 2 in Table VIII were made in apparatus No. 2, which is so constructed that the supply of water vapour to the place of crystal formation is quite abundant. In case of No. 3 which was made in apparatus No. 4, T_w was also high and was continued at the high value for a long

Table VII. Irregular form and side planes.

Apparatus number	No.	Photo. No.	Experiment number	Form of crystal	T_r	T_a			T_w			t	Rate of growth mm/hour
					mean	initial	middle	final	initial	middle	final		
No. 1	1		T 193–194	*side planes	−26°C	−17°C	−18°C	−19°C	+5°C	+15°C	+4°C	20 h	0.08
	2		T 258–259	*side planes	−28	−19	−21	−23	+12	+10	+ 8	17 h	0.18
	3		T 256–257	irregular form	−29	−21	−21	−19	+ 8	+14	+18	3 h	0.7
	4		T 292–293	*irregular form	−29	−24	−24	−23	+ 7	+15	+21	2 h	1.3
	5	31	T 214–217	irregular form	−30	−23	−23	−23	+ 8	+10	+12	1 h	1.3
	6		T 277–279	side planes	−30	−22	−23	−24	+ 7	+ 8	+ 8	2 5 h	0.6
	7		T 314–316	*side planes	−30→−40	−28	−24	−36	+ 6	+ 6	− 5	20 h	0.14
	8		T 27–30	*side planes	−33	−25	−29	−29	+ 6	+15	+15	6 h	0.25
No. 2	9	30	T 300	*side planes	−30	−26	−24	−22	+ 7	+ 6	+ 5	20 h	0.17

mean 0.52 mm/hour

* Germ of crystal was made very slowly by leaving the filament in the apparatus overnight.

Table VIII. Miscellaneous.

Apparatus number	No.	Photo. No.	Experi-ment number	Form of crystal	T_r	T_a			T_w			t	Rate of growth mm/hour
					mean	initial	middle	final	initial	middle	final		
No. 2	1		T 3–4	*needle	−23°C	−18°C	−12°C	−8°C	+10°C	+15°C	+20°C	2.5 h	—
No. 2	2		T 14–16	*needle	−25	− 9	−10	−10	+20	+16	+16	18 h	0.7
No. 4	3	32	M 318–319	*needle	−22	−16	−15	−14	+17	+20	+21	12 h	0.33
No. 2	4		T 5–6	*cup crystal	−23	−18	−12	− 8	+10	+15	+20	2.5 h	—
No. 2	5		T 17	*cup crystal	−25	− 9	−10	−10	+20	+16	+16	18 h	0.4
No. 1	6		T 216	cup crystal	−30	−23	−23	−23	+ 8	+10	+12	2 h	0.5
No. 3	7	25	T 75	dendritic and sector	−24	−23	−22	−21	+ 5	+ 8	+12	3 h	2:1
No. 1	8		T 96	fern-like and sector	−25	−16	−15	−12	+10	+12	+13	2 h	3.5:1
No. 4	9	26	M 366	dendritic and plate	−25	−16	−15	−16	+11	+12	+13	4 h	2.5:1
No 4	10		M 32	dendritic and sector	−23	−18	−18	−17	+ 8	+14	+18	1.5 h	2.5:1

* Germ of crystal was made very slowly by leaving the filament in the apparatus overnight.

time. The former conclusion that needle crystals are made when the air temperature is moderately high and the supply of water vapour is abundant, seems in the main to be correct. Nos. 4–6 in Table VIII show the conditions for the formation of cup crystals. They are sometimes produced under the same conditions as the needle formation. Nos. 7–10 treat peculiar forms of crystal, the half portion of which belongs to a dendritic type while other portion is a sector or plate. Two examples are shown in Photos. 25 and 26, Pl. IV. The figures in the last column of the Table show the ratio of the dimenisons of these two parts of different form.

Looking through Tables IV–VIII, the following points are to be noticed:

i) the mean rate of growth is
   4.6 mm/hour for fern-like crystals,
   1.3 ,, for ordinary dendritic and broad branch type,
   0.7 ,, for sectors and plate,
   0.5 ,, for side planes and irregular form,
   0.5 ,, for needles,

ii) fern-like and ordinary dendritic crystals are made with T_a between $-15°C$ and $-23°C$, while T_a below $-23°C$ it is difficult to obtain these sorts of crystals even if various values of T_w are chosen; that is, for a wide range of the rate of supersaturation,

iii) with T_a below $-23°C$, crystals are likely to develop into an irregular form or a type of side planes,

iv) for producing a certain type of crystal, T_w varies in a wide range for a given value of T_r, which may be explained by the difference in the mode of convection of the supersaturated air in the apparatus,

v) the form of the germ or the early stage of the crystal has some powerful influence upon the subsequent growth of artificial snow.

The external conditions for determining the form of the crystal are not simple. The controllable elements in this experiment are T_r and T_w. T_a is determined by T_r, T_w, the configuration of the apparatus and the mode of convection. The last mentioned is chiefly determined by the preceding three elements, but it is strongly influenced by fluctuation in general conditions. Thus T_a is controlled only in a statistical sense. At present the authors refrain from any conclusion as to the conditions for determining the form of the crystal. Experiments are now in progress for examining the effect of fluctuation in condition upon the form of the crystal.

10. Experiments carried out with the room temperature at nearly $-40°C$.

When the room temperature is very low, at nearly $-40°C$, the form of snow crystals produced is quite different from the former cases described in the preceding article. No beautiful flakes could be obtained in the present series of experiments, although the degree of supersaturation was varied within a wide range, T_w was altered within a range between $+11°C$ and $-6°C$. When the rate of supply of water vapour was moderate, the crystal developed into an assemblage of side planes and columns as shown in Photo. 33, Pl. VI. Increasing the rate of supply of water vapour, the crystal showed a tendency to grow into the form of an irregular assemblage of small crystals, one example being reproduced in Photo. 34, Pl. VI.

The mode of germ formation on the filament was like that when T_w was increased rapidly as decribed above in section 4c. It was usually observed that many germs appeared on the filament in about half an hour after its introduction into the apparatus. These germs were sometimes so abundant in number that they covered the filament completely appearing as in the photograph reproduced in Photo. 2, Pl. I. It was extremely difficult to get a few insolated germs on the filament with this low room temperature.

Two sets of apparatus, No. 1 and No. 2, were used. Apparatus No. 2 was so constructed as to give a greater rate of supply of water vapour to the place of crystal formation than does the former, T_r and T_w respectively being chosen the same for both cases.

The conditions under which the crystals were produced have been tabulated in Table IX. In the Table t shows the time measured from the moment when the filament was set in the apparatus. In the two cases of Nos. 1 and 5 in the Table, T_r was initially kept at nearly $-30°C$ so that isolated germs were formed with this value of T_r, and then T_r was reduced to nearly $-40°C$. This method was convenient for getting isolated germs on the filament. Sometimes the water in the reservoir was frozen, in which cases T_w showed a value below $0°C$. From the data in the Table one will see that a moderate supply of water vapour produced an assemblage of side planes and columns, while an abundant supply yielded an irregular assemblage of small crystals. These sorts of crystals are observed also in the case of natural snow.

In order to examine the effect of changing the rate of supply of water vapour more closely, a series of experiments was carried out by introducing

Table IX.

App. No.	No.	Photo. No.	Form of crystal	T_r	T_a	T_w	t
No. 1	1			−30°C	−28°C	+6°C	0
			left overnight, germs formed	−30	−24	+6	19 h
				−42	−35	−1.5	21 h
			spatial assemblage of side planes	−43	−36	−6	22 h
	2	33		−40	−38	0	0
				−41	−37	−6	25 m
			assemblage of side planes and columns	−40	−33	+2	2 h 50 m
	3			−40	−33	0	0
				−41	−31	−2.5	30 m
			irregular assemblage of small crystals	−41	−30	+1	1 h 10 m
	4			−40	−33	+2	0
				−40	−31	+6	20 m
			many germs cover the filament	−40	−31	+9	30 m
			irregular assemblage of columns and plates	−40	−31	+9	1 h 15 m
No. 2	5	34		−30	−29	+6	0
			germs formed	−42	−32	−3	3 h
			irregular assemblage of small crystals	−40	−30	+5	4 h
	6			−41	−39	−2	0
			many germs cover the filament	−41	−31	−0.2	1 h 40 m
			assemblage of small plates and columns	−40	−31	0.0	2 h 20 m
	7			−41	−30	+6	0
			many germs cover the filament	−40	−29	+5	25 m
			irregular assemblage of plates and side planes	−40	−27	+11	1 h 5 m

a stop diaphragm in the apparatus. Reducing the upward convection of water vapour by this means, it was possible rather easily to obtain several isolated germs on the filament. The conditions of crystal formation have been tabulated in Table X.

In case of No. 1 the filament was left overnight in the apparatus and the crystal developed to the state shown in Photo. 35, Pl. VI in three hours after the germ formation. In this case the rate of supply of water vapour

Table X.

App. No.	No.	Photo. No.	Dia. of stop	Form of crystal	T_r	T_a	T_w	t
No. 1	1		0.6 cm	left overnight	−38°C	−35°C	+3°C	0
				germs formed	−33	−32	+10	15 h
					−37	−30	+12	16 h
		35		columns with side planes	−40	−32	+11	18h
No. 1	2		1 cm		−43	−36	+7	0
					−40	−38	+4	2h
		36		assemblage of columns and small planes	−40	−36	+16	3h 30m
No. 1	3		1 cm		−37	−35	−4	0
				germs observed	−43	−41	0	30m
					−40	−35	+12	2h 40m
		37		irregular form of amorphous appearance	−39	−35	+12	4h 10m

was smallest. The form of crystal is an assemblage of columns with side planes. Comparing Photo. 35 of this paper with Photo. 35 of report No. 7, which is an example of natural snow of this type, one will see no essential difference among their forms and structures. The crystals obtained in experiment No. 2 in the Table are shown in Photo. 36, Pl. VI. This type is quite similar in structure to that reproduced in Photo. 37 of report No. 7, which is composed of an assemblage of columnar crystals associated with small planes. This type of snow is observed often in a high mountain district, where the temperature is very low. These crystals in their newly fallen state have the appearance of a heap of flour. The result of the present experiment is consistent with the supposed mechanism of the formation of this "flour snow" observable in nature. Experiment No. 3 gave a peculiar form of irregular snow. In this case the filament was set at the centre of the circular hole of the stop diaphragm, so that the filament was just in the position where the water vapour brought upward by natural convection converges. The crystal developed into a peculiar form as shown in Photo. 37, Pl. VI. This sort of crystal belongs to the amorphous particles enumerated in the general classification proposed in report No. 8. These apparently amorphous particles are often observed in nature, although they have hitherto been rarely reported in the literature on snow crystals. A typical example of this sort of natural snow is reproduced in Photo. 38. This photograph was taken by Mr. K. Nakata in South

Saghalien, where the climate is colder than that at the places of our observation. Best thanks are due to him for lending this important photograph. A close examination of the photograph shows that this crystal is not an amorphous particle in the literal sense. It looks to be made up of many dendritic branches growing in thick clusters and covered with numerous droplets.

From the results of this series of experiment it is made clear that the assemblage of side planes and columns or the flour-like snow is made when the temperature is low and the supply of water vapour is scanty or moderate, while the snow takes the form of a peculiar type of amorphous particle if the supply of water vapour is abundant.

11. Supplementary notes on the mechanism of crystal growth.

During the course of this series of experiments about one thousand photographs of various sorts of crystals were taken, among which some photographs in addition to those already referred to seem to be worth reproduction, as they show the mechanism of crystal growth very clearly. They are reproduced in Photos. 39–50, Pls. VII and VIII. Brief explanations will be given of these photographs.

a) Thick and thin sectors.

An example of thick sectors is shown in Photo. 39 and one of thin sectors in Photo. 40. The conditions of the formation of these crystals are given in Nos. 3 and 4 of Table VI. The thick sectors show a special design of inner structure. A close examination of this thick sector shows that it is made up of two thin sectors one overlapping close on top of the other. This twofold structure is a result of the development of a thick plate in a skeleton form. A more marked example of this type is described below in section *e*). The thin sector is made of a simple plate sheet. Accordingly the former needs a more abundant supply of water vapour for its formation than does the latter. The data in Table VI show that mean T_w is $+18°C$ in case of the thick sectors, while it is only $+8°C$ for the thin ones. The rate of growth of the former is about one half that of the latter. It appears that the thick type is made with higher T_a, the mean being $-13°C$ in this example, while the thin type is likely to be produced with lower T_a, the mean of which is $-20°C$ in this case. This tendency is also observed in case of natural snow. It is well known that snow crystals tend to take the form of a very thin flake when the climate is severely cold.

b) The development of a dendritic branch from a plate.

Photo. 41, Pl. VII shows nicely the initial stage when a dendritic branch begins to grow from a corner of a plate. This was made in apparatus No. 4 with the mean T_w at $+11°$C, T_r at $-28°$C and T_a at $-20°$C. The photograph is an oblique view of the state at 4.5 hours after the formation of the germ. The hexagonal part is essentially a skeleton form of prism as shown in No. 11, Fig. 10. The ice material filling up the spaces is in this case very thin and the general appearance is like two shallow hexagonal dishes of thin make attached to each other at their bottoms. Two dendritic branches extend out from each of two corners facing each other. This photograph shows that the dendritic branches develop under the condition that the rate of growth is larger in the direction of the subaxes of the hexagonal system of the ice crystal.

c) Accumulation of short columns.

In natural snow it is sometimes observed that a crystal is composed of many columns standing one above another with several sheets of well developed dendritic planes attached normally to the column. One example will be seen in IV–1 of the general classification proposed in report No. 8. Photo. 42 is a remarkable example of this sort of crystal produced artificially in apparatus No. 4. In the photograph, the straight lines extending upward normally from the ends of the component columns are the side views of the plane dendritic branches. The parallel arrangement of these planes shows that the principal axes of all the component columns lie in one direction. Another example of a similar crystal, which was produced in the same experiment as the former, is shown in Photos. 43 *a* and *b*. In *a* the side view of the crystal is shown and in *b* the front view of the same. In this case the short columns may be better described as thick plates of skeleton form.

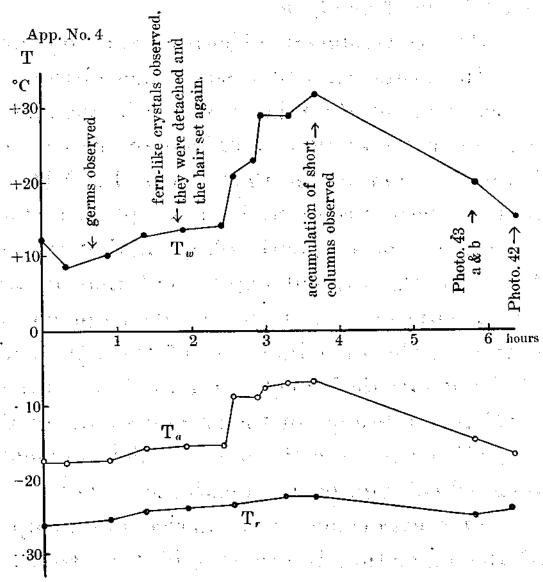


Fig. 15.

The conditions under which these crystals were made may be seen in Fig. 15. In this case T_r was kept throughout between $-24°C$ and $-26°C$. Initially T_w was adjusted so that the condition was favourable for the development of dendritic branches; that is, T_w was raised gradually from $+7°C$ to $+14°C$ in about two hours, the corresponding T_a having been at nearly $-16°C$. Under these conditions the crystals on the filament developed, as expected ,into a fern-like form. These crystals were broken off on purpose and the filament was again set in the apparatus. Then T_w was raised quickly to $+32°C$ in about one hour. T_a went up with T_w and reached $-7°C$ in consequence of the excessive supply of warm vapour. Many crystals in the form of an accumulation of short columns were produced under these conditions both on the filament and on the thin thermometer for measuring T_a. The filament was taken out so that photographs might be taken, but the thermometer was left untouched. Reducing T_w gradually to $+15°C$, T_a came back to the former value $-16°C$. Examining the crystals on the thermometer, beautiful fern-like branches were found extending out in the plane of the end face of the column. Photos. 42 and 43*b* show this state. From the results above described it will be inferred that the accumulation of short columns is obtained when the temperature is relatively high and the supply of water vapour is abundant, while for the production of fern-like crystals the temperature must be moderately low.

d) Development of cup crystals on plane branches.

In natural snow it is sometimes observed that a dendritic plane crystal appears under the microscope to be hemmed with black ribbons. Similar crystals are sometimes obtained in the case of artificial snow, one example being represented in Photo. 44*a*, Pl. VIII. Formerly it was considered to have been produced by a simple attachment of cloud particles to the margin of the dendritic plane, and it was so in most cases. But it was found in the present experiment that in some cases this type of crystal was produced as a result of development of cup crystals on the plane branches, the principal axis of the cup being perpendicular to the plane of the dendritic branch. Photo. 44*b* is a side view under a large magnification of a branch of the crystal shown in Photo. 44*a*. In the photograph one will clearly see the mode of development of cup crystals as a skeleton form of column, on the dendritic planes.

This experiment was carried out in apparatus No. 4, and the course of the formation is graphed in Fig. 16. First T_w was raised gradually from $+7.5°C$ to $+12.5°C$ and a dendritic form was obtained. Then T_w

was brought up rather quickly to $+27°C$, T_a having been raised to $-9.5°C$ as the result of the abundant supply of warm vapour. Cup crystals were produced under this condition and Photos. 44 *a* & *b* were taken. Then the crystal was again set back in the apparatus and the experiment was continued. T_w was reduced to $+21°C$ and consequently T_a came back to $-15°C$, near to the former value for dendritic crystal development. After one hour the crystal was taken out for taking Photo. 45, when it was found that new dendritic branches extended out from the margin of the original crystal. The crystal shown in Photo. 44*a* is seen in the central part of the crystal reproduced in Photo. 45. The result of this experiment supports the argument given in the preceding section *c*); that is, for the production of fern-like crystals the temperature must be moderately low, the favourable condition being between $-15°C$ and $-20°C$, while the cup crystals are obtained with higher temperature and an abundant supply of warm vapour.

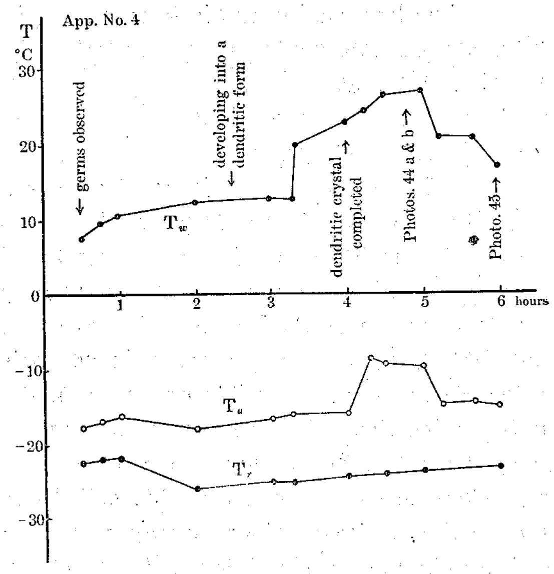


Fig. 16.

e) Thick plates at the terminals of dendritic branches.

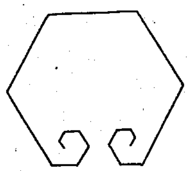
The terminal portion of a dendritic branch sometimes develops into a peculiar form as shown in Photo. 46*a* or 47*a*. This is a thick plate of skeleton form as shown schematically in No. 9, Fig. 10. Side views of crystals shown in Photos. 46*a* and 47*a* are given in Photos. 46*b* and 47*b* respectively. These photographs show the structure very nicely. These crystals were made with mean T_r at $-26°C$, mean T_a at $-21°C$ and mean T_w at $+10°C$. The temperature values were kept rather constant in this case, varying within a range of 4°C during six hours of the formation of the crystals.

f) Skeleton form of a prism.

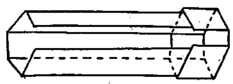
One example of the skeleton form of a prism is shown in Photo. 10, Pl. I. Another good example is reproduced in Photo. 48, Pl. VIII. The latter crystal was made in apparatus No. 4, with constant T_w at $+11°C \pm 1°C$ and T_a at $-20°C \pm 1°C$, T_r increasing from $-30°C$ to $-25°C$ gradually. It took seven hours for the growth of the crystal to the stage shown in the photograph.

g) Extension of side planes of a prism.

When the side planes of a prism develop to their full extent, the crystal grows into the form of a hexagonal scroll. According to SELIGMAN[1] this type of crystal is often observed among crevasse hoar crystals. He says that it is comparatively common in regions where low temperature exists and that it is found anywhere a large cooled space is formed in which water vapour can accumulate under calm, still conditions. The conditions under which the artificial snow with extended side planes is produced, are in agreement with the conditions above mentioned. As shown in Table VII, these crystals are often obtained from the germs which are made under calm, still conditions by leaving the filament in the apparatus overnight. The favourable T_r is nearly $-30°C$, that is lower than the case for dendritic development.



a) Horizontal section of a crevasse hoar, after Seligman.



b) Sketch of the crystal shown in Photo. 49.

Fig. 17.

Fig. 17a, cited from SELIGMAN's book, shows a horizontal section of a typical crevasse hoar in a scroll form. Fig. 17b is a sketch of the crystal shown in Photo. 49, Pl. VIII. This crystal was made by a slow process with T_a at $-30°C$ and T_w varying from $+4°C$ to $+9°C$ in six hours. Another example of this type of snow is shown in Photo. 50, which was made in the same experiment as Photo. 49.

12. Crystals made by a very slow process.

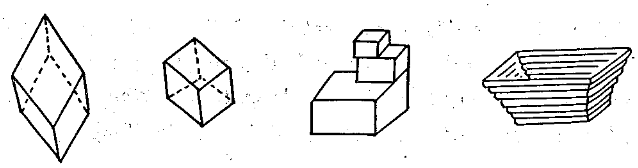
The crystal symmetry of ordinary ice has been long a question among physicists and crystallographers. *X*-ray investigations carried out by

1) G. SELIGMAN, Snow structure and ski fields, pp. 73–76.

BARNES[1] confirmed the view proposed by Tammann, Bridgman, Bragg and others that ordinary ice crystals belong to the hexagonal system. MÜGGE[2] is of different opinion on this point and he considers that ice is to be assigned to the rhombohedral system. Recently SELJAKOV[3] found by the X-ray method that ordinary ice exists in two different modifications, as α-hexagonal and β-rhombohedral ice. Ice was prepared by freezing distilled water from the surface in open air, and α ice was favourably formed when the temperature of the surrounding air was somewhat below zero and β ice when there was a considerable frost, say below $-10°$C.

The atuhors tried to produce the ice crystals of the simplest form by making them grow by the very slow process. The example shown in Photo. 51, Pl. IX is one of the crystals thus obtained. It takes the form of a hexagonal column and there is little doubt that this crystal belongs to the α-hexagonal ice type. This was made in apparatus No. 4 with a stop diaphragm and it took 70 hours for the development to the stage shown in the photograph. T_r was throughout kept at $-30°$C and T_w at $0°$C.

Photos. 52 and 53 show crystals which apparently assume a rhombohedral form. The schematical sketches of them are shown in Fig. 18, *a* and *b*. They were made in apparatus No. 1 with T_r at $-30°$C and mean T_w at $+9°$C. The photograph shows the stage at 31 hours after the beginning of the experiment. In this case the supply of water vapour was not so small as in the previous case and consequently the rate of growth was slighlty larger. The crystals show the tendency to develop into a skeleton form. Judging from the form, it will be natural to consider that these crystals are the β-rhombohedral ice of Seljakov.



a) Photo. 52. b) Photo. 53. c) Photo. 54. d) Photos. 55–57.

Fig. 18.

The crystal shown in Photo. 54 was made in apparatus No. 1 with T_r at $-28°$C and T_w increasing from $-6°$C to $+7°$C in 20 hours. As

1) W. H. BARNES, Proc. Roy. Soc., A, 125 (1929) 670.

2) O. MÜGGE, Centrl. Mineral., 137 (1918).

3) N. J. SELJAKOV, Comptes Rendus (Doklady) de l'Academie des Sciences de l'URSS. (1936) No. 7, (1937) No. 4.

shown by the schematical sketch Fig. 18*c*, this crystal apparently assumes a cubic form. The hoar crystal in a cubic form was reported by Geinitz, Nordenskjöld and others more than half a century ago, and the existence of a modification of ice that is to be assigned to the cubic system has been assumed by many scientists. By a kind letter of Prof. John Satterly of the University of Toronto, the authors were told that Prof. Ernst Cohen of the University of Utrecht recently found a new variety of ice crystal of cubic system. The crystal shown in Photo. 54 may belong to this variety of ice. The apparently cubic form, however, can be obtained among the crystals of rhombohedral system, and conclusions may well be withheld until *X*-ray investigation is carried out with respect to these special ice crystals.

Hoar crystals in the form of a rectangular cup are sometimes observed in nature. One example is shown in Photo. 55, Pl. IX. This photograph was taken by Mr. Hatakeyama at Toyohara, south Saghalien. The authors are much indebted to him for his kindness in sending the picture with permission for publication. Similar crystals are also observed among the artificially produced ones. Two examples are reproduced in Photos. 56 and 57, Pl. IX. The crystal in Photo. 56 was made in one hour in apparatus No. 4 with T_r at $-30°C$ and T_w at $+9°C$. The crystal shown in Photo. 57 was found adhering to the inside surface of the copper sheet which was used as a cover of the apparatus. The apparatus was the old one used in the experiments described in report No. 10. T_r was $-24°C$ and mean T_w was $+8°C$, the crystal being obtained in two hours. The structure of these crystals is clearly shown by the schematical sketch Fig. 18*d*.

Summarizing the results, the crystals of simple form, which show the characteristics of hexagonal, rhombohedral and cubic systems respectively, were obtained by slow sublimatic condensation. The conditions of the formation of these three sorts of ice are not yet clarified.

13. Sublimation of snow crystal.

In report No. 7 the authors introduced the view of SHEDD[1], WEGENER[2] and others that a dendritic crystal is first formed in a sufficiently super-saturated zone of the atmosphere and then the space between the skeleton branches is filled up with ice while the crystal is falling through a less

1) Shedd, Month. Weath. Rev., 47 (1919) 691.

2) Wegener, Thermodynamik der Atmosphäre, dritte Auflage, Leipzig, 1928, p. 248.

supersaturated layer, transforming the dendritic crystal into plate form having symmetrical patterns inside. Next strata of a sufficient supersaturation will add other dendritic appendages. This theory appears to explain the origin of the patterns inside a plate very nicely, and the authors tried to confirm this theory by making artificial snow. The results of the experiments showed that this idea is in the main correct so far as the general tendency of development of snow crystal is concerned, but the mechanism producing the patterns inside a plate seems to be a little different from the above theory.

First the transformation of a dendritic crystal in a less supersaturated atmosphere was studied experimentally. The crystal shown in Photo. 22, Pl. IV was used. As described in section 8*a*), this crystal was made in apparatus No. 1 with T_r at $-22°C$ and T_w at $+7°C$. After taking Photo. 22 the crystal was returned to the apparatus and T_w was reduced to $+4°C$. The crystal was left untouched for 39 hours under this condition, T_a varying between $-20°C$ and $-22°C$. The crystal changed into a form reproduced in Photo. 58, Pl. X. It is observed that the space between the skeleton branches is filled up with ice to a certain extent, but the marked change takes place in the thickness of the branch. The component blades of the branch transform into thick plates like those of the example shown in Photos. 46 and 47, Pl. VIII. The transformation of a dendritic crystal into a simple plate did not happen in this case; that is when the degree of supersaturation was reduced to nearly two-thirds that of the original value.

A similar experiment was carried out with respect to a crystal with broad branches. The crystal reproduced in Photo. 29, Pl. V was used. The conditions of the formation of this crystal are shown in Table V. After taking Photo. 29 this crystal was kept in the apparatus, the water in which was poured out so that the crystal was exposed to an atmosphere without supersaturation. It was left untouched for 42 hours at nearly $-23°C$, and then examined under a microscope. The original crystal had degenerated into a rounded form and most of the internal structure had disappeared, as expected from the action of the sublimation of the pointed portion. It was, however, not transformed into a plate. In order to ascertain the second step of development of branches, water was again poured into the apparatus and a similar experiment was carried out again. Increasing T_w from $+2°C$ to $+9°C$ in one hour and a half, appendages of sector form were added to the corners of the deformed crystal. The final state is shown in Photo. 59, Pl. X, in which one will see the degenerated form of the crystal in Photo. 29 in the central part of the crystal in Photo. 59. The appendages thus obtained are quite similar in form and structure to those of some natural snow; for example, Photo. 5*b* of report No. 5.

The rate of sublimation of fern-like crystals was measured under various conditions. Exposing the crystal on a glass plate to the atmosphere in the cold chamber, it was found that the sublimation was fairly rapid even when the temperature was very low, at nearly $-20°C$. The atmosphere in the chamber is considered to be saturated with water vapour at that temperature, because the wall of the chamber is covered with frost crystals. Usually the crystals disappeared after five or six hours under this condition. One example is shown in Photos. 60 and 61, Pl. X. Photo. 60 shows the crystal immediately after its formation. This crystal was made in apparatus No. 4 with mean T_r at $-22°C$, mean T_a at $-16°C$ and T_w increasing from $+5°C$ to $+18°C$ in three hours. Being exposed to the saturated atmosphere at $-19°C$ for four hours, the linear dimensions were reduced to nearly one half of the original values. The sharp outline and the internal structure were lost as shown in Photo. 61.

When the crystal was kept in a bottle with a stopper, the rate of sublimation became smaller. A fern-like crystal was produced under similar conditions as in the preceding case. The form of the crystal immediately after its formation is shown in Photo. 62. This crystal was kept in a glass bottle of one litre capacity, by being suspended with a filament. It was left in the cold chamber, the temperature of which varied between $-16°C$ and $-20°C$, and its deformation was examined at irregular intervals. The sublimation took place at a far slower rate than in the previous case. Photo. 63 shows the state at 20 hours after being put in the bottle.

It is well known that the vapour pressure in equilibrium with pointed parts or sharp edges is larger than the so called saturation pressure, which means the vapour tension in equilibrium with a plane surface. In order to keep the artificial snow crystals as long as possible in the original form, a vessel was designed. A glass bottle with a stopper was chosen and frost crystals of dendritic form were made to grow in clusters, covering the whole interior of the bottle. When a snow crystal is suspended therein, it is exposed to the atmosphere which is to some degree supersaturated with water vapour. For convenience this vessel is called a "preserving bottle." When a dendritic crystal of artificial snow is kept in this preserving bottle, the diminution in dimension takes place at a much smaller rate. Usually

Table XI.

Mode of preserving the crystal	Temperature at which kept	Form of crystal	Diminution in linear dimension
Left on a glass plate and exposed to the cold atmosphere.	$-19°C$	fern-like (Photos. 60 & 61)	0.48 of original dimension after 4 h.
	$-20°C$	ordinary dendritic	0.66 of original dimension after 50 m.
	$-20°C$	plate with simple extensions	0.83 of original dimension after 1 h.
	$-26°C$	plate with sector extensions	0.35 of original dimension after 5 h.
	$-28°C$	plate with dend. ext. with droplets	0.75 of original dimension after 1 h.
Kept in an empty bottle	$-16°C \sim -20°C$	fern-like (Photos. 62 & 63)	0.84 of original dimension after 20 h.
Kept in a preserving bottle.	$-35°C$	ordinary dendritic	0.83 of original dimension after 68 h.
	$-25°C \sim -30°C$	branches in sector form	0.9 of original dimension after 43 h.
Kept in a bottle containing P_2O_5.	$-16°C$	branches in sector form	0.2 of original dimension after 1 h 25 m.
	$-26°C$	broad branches	0.2 of original dimension after 1 h 20 m.

it takes about 50 hours for 10% reduction in linear dimension. The fine internal structure, however, is lost in ten hours or less even in this case. Different to the condition above described, a bottle containing a small quantity of P_2O_5 was tried. In this case the crystal sublimates, as expected, very rapidly and usually disappears in less than two hours.

The summary of this series of experiment is shown in Table XI. The following conclusions are obtained from the data in the Table. The sublimation of a snow crystal proceeds rather quickly in the atmosphere saturated with water vapour even when there is a severe frost, say at $-20°C$. It is accelerated considerably by gentle ventilation in the surrounding atmosphere. The snow crystal keeps its original form and dimension for a long time, twenty or thirty hours, when it is kept in atmosphere of a slight supersaturation, but even in this case the fine internal structure or the sharp outline is lost after several hours.

From the results described above it is made clear that the snow crystal of delicate form and design, especially the fern-like type, cannot be *developed* in the atmosphere even when it is supersaturated to some extent.

At the present stage of their studies the authors consider that these crystals of snow are formed in an unstable state by the *mixing* of the air at low temperature and that saturated with warm vapour. Taking this view as a working hypothesis, one of the most important factors determining the form and structure of snow crystal is the microscopic fluctuation in conditions under which the crystal is made to grow. Experiment is now being carried on in this line and the results will be published in the following report.

Summary.

The artificial production of snow crystals was carried on in the cold chamber laboratory by using improved apparatus. Four pieces of apparatus were designed to give different modes of convection of water vapour, and the authors succeeded to some extent in getting any required sort of snow crystal in a reproducible manner. The mode of convection of air in the apparatus was studied by measuring the temperature at various places inside the apparatus. The theory and practice for getting isolated germs of snow crystal on the suspending filament were discussed. The early stage of snow crystals was studied and it was found that almost all types of snow crystal are seen among the copious variety of artificial crystals in their early stages. The influence of the form of the early stage on the subsequent growth of snow crystal was discussed. Describing the details of the experimental procedure in making the artificial snow, the effect of the convection of air upon the form of crystal was examined.

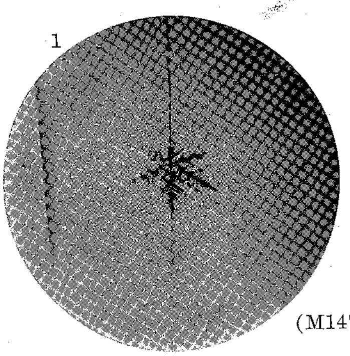
The results of experiments carried out with the room temperature between $-20°C$ and $-30°C$ showed that the form of crystal is determined by the rate of growth of crystal. The mean rate of growth was found to be 4.6 mm/hour for fern-like crystals, 1.3 mm/hour for ordinary dendritic and broad branch type, 0.7 mm/hour for sectors and plate and 0.5 mm/hour for side planes and irregular form. The favourable conditions for the development of crystal in a dendritic form was studied. The similar experiments were carried out with the room temperature at nearly $-40°C$ or below, and it was found that the form of crystal was quite different from that obtained in the foregoing case.

Some experiments were conducted for the purpose of getting the simplest form of ice crystal and the apparently hexagonal, rhombohedral and cubical form of ice crystals were obtained. The change in form of snow crystal due to the atcion of sublimation was studied experimentally

by the use of artificial snow, and a working hypothesis is proposed to the effect that the snow crystals can be developed by the unstable mixing of the air at low temperature and that saturated with warm vapour.

In conclusion, the authors wish to express their best thanks to the Nippon Gakuzyutu-sinkôkai for the financial assistance for this research.

1



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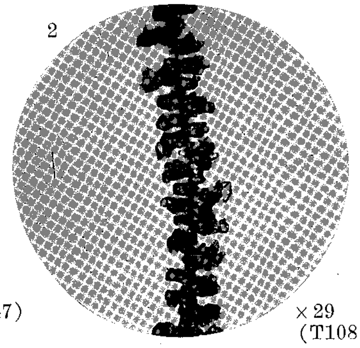

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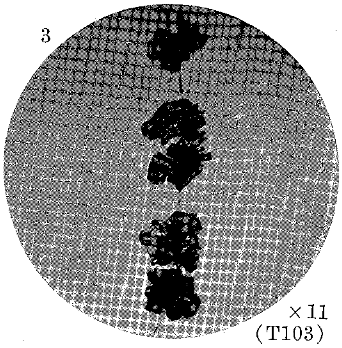

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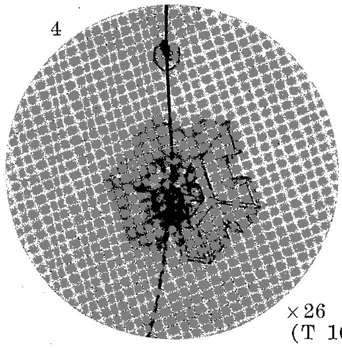

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(T 163)

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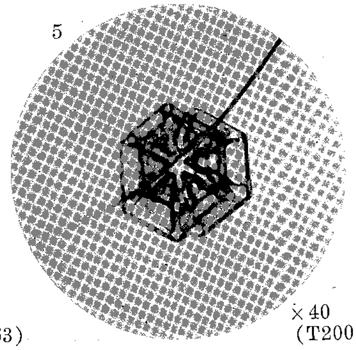

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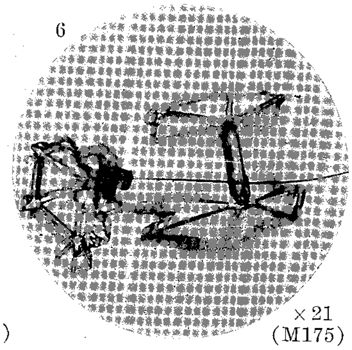

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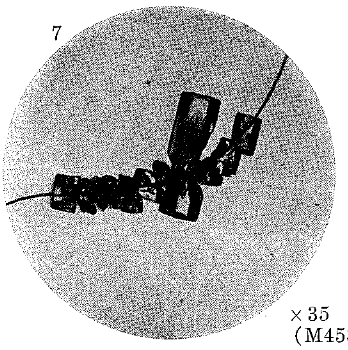

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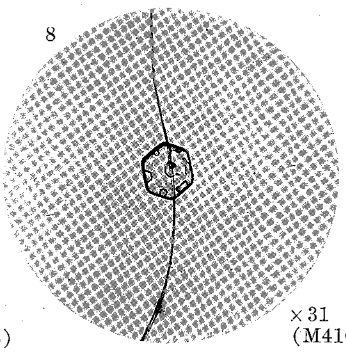

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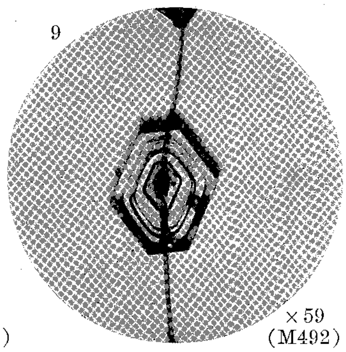

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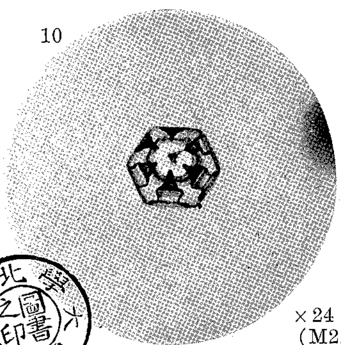

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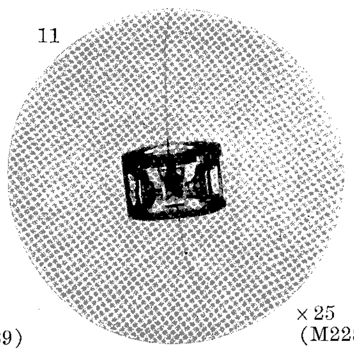

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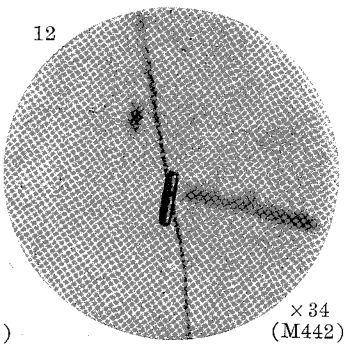

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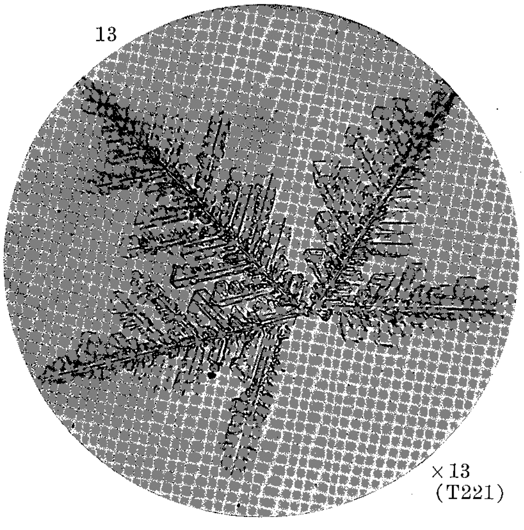

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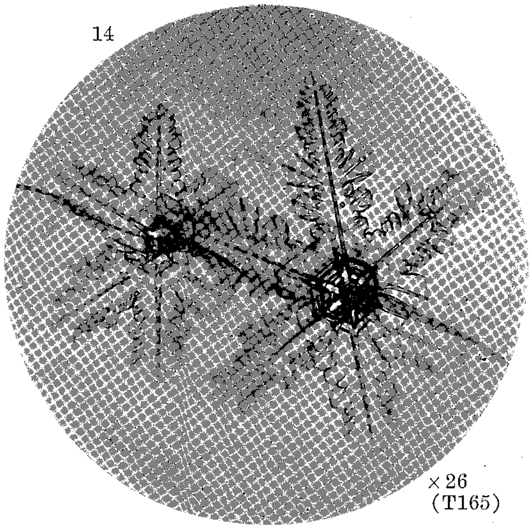

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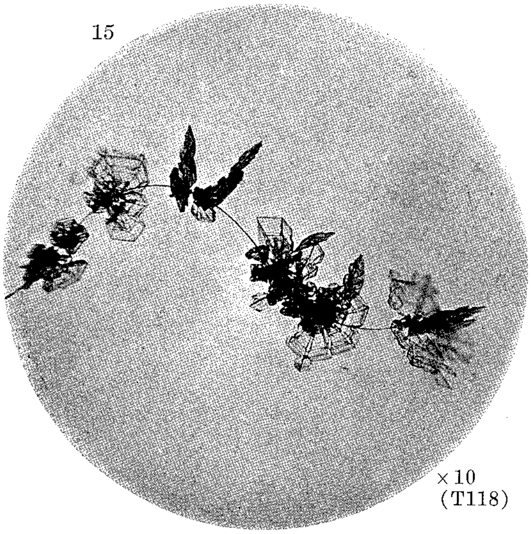

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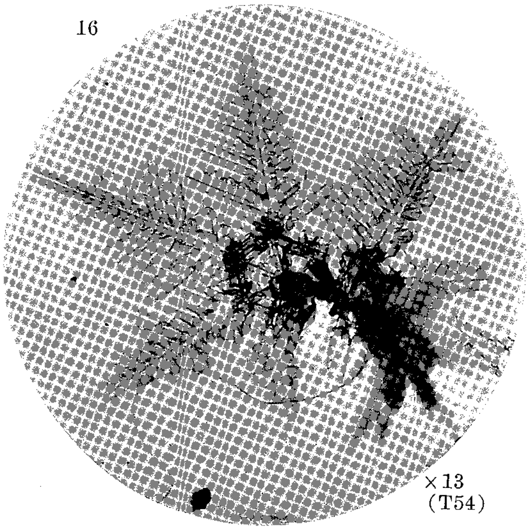

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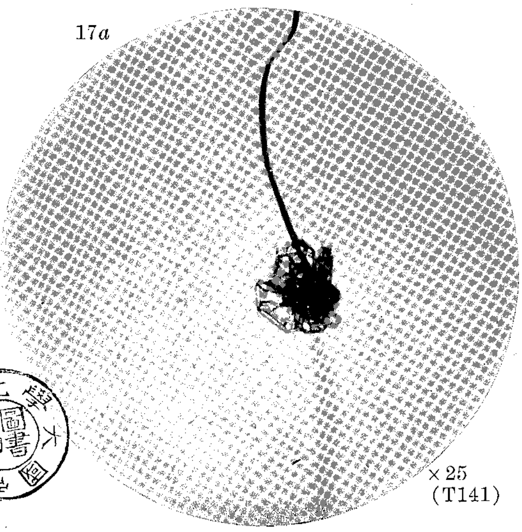
17*a*



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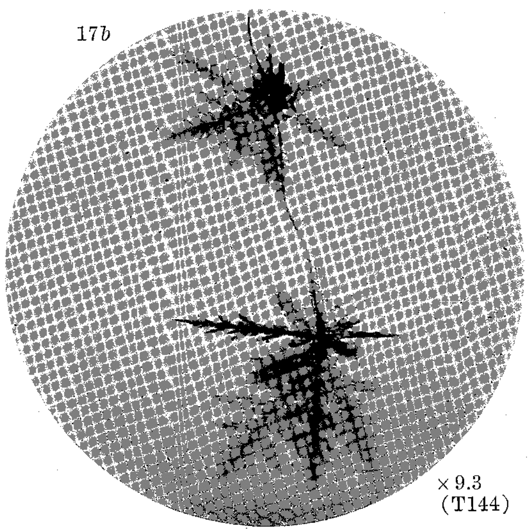
17*b*



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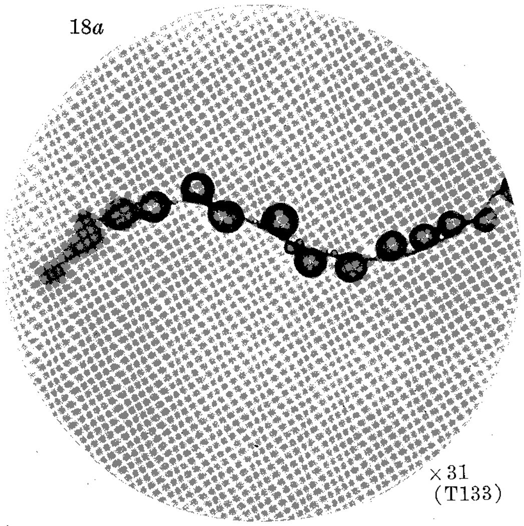

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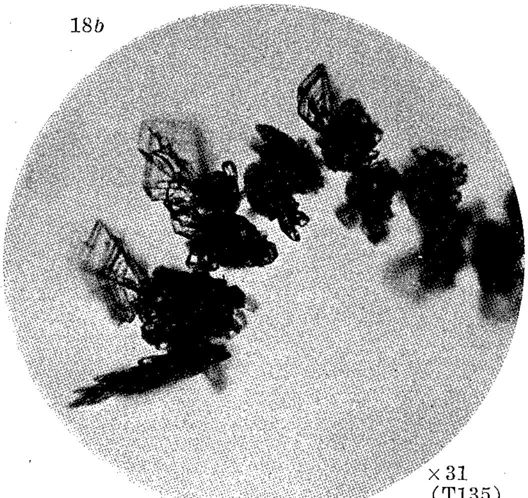
18*b*



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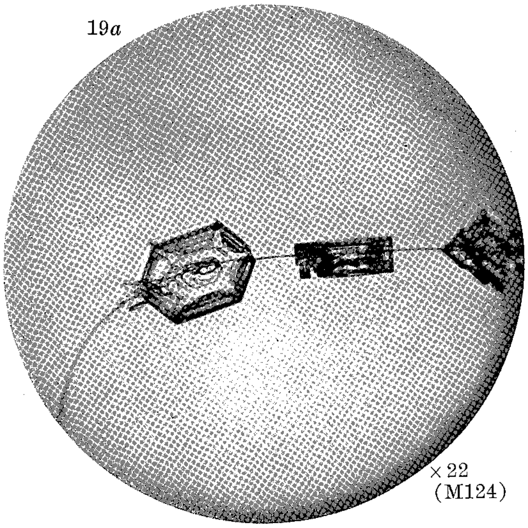

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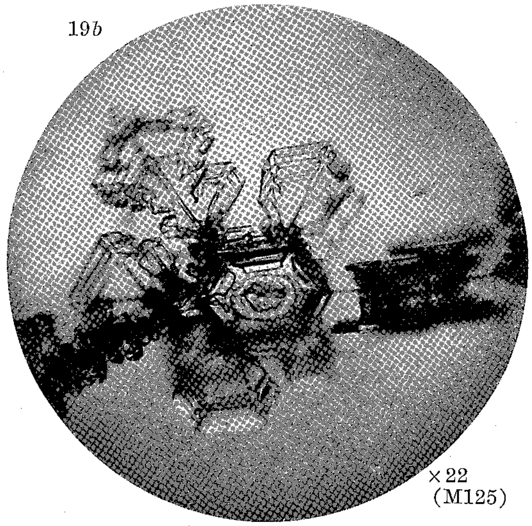
19*b*



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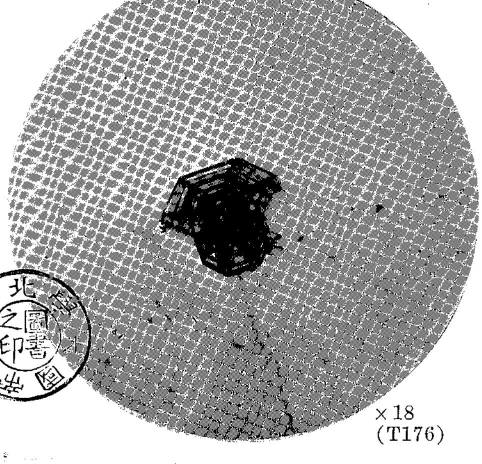
20*a*



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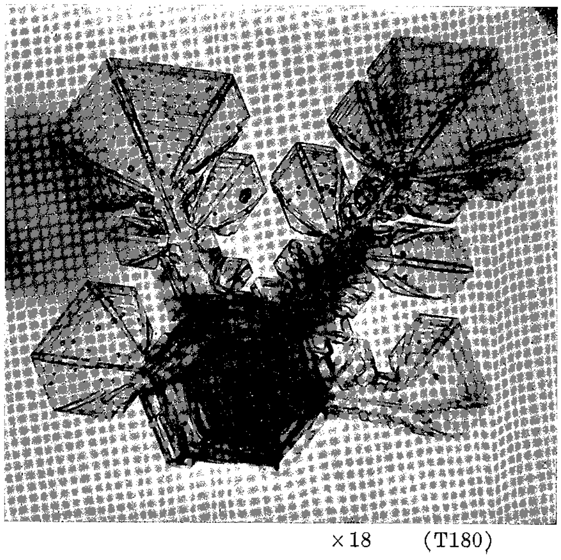
20*b*



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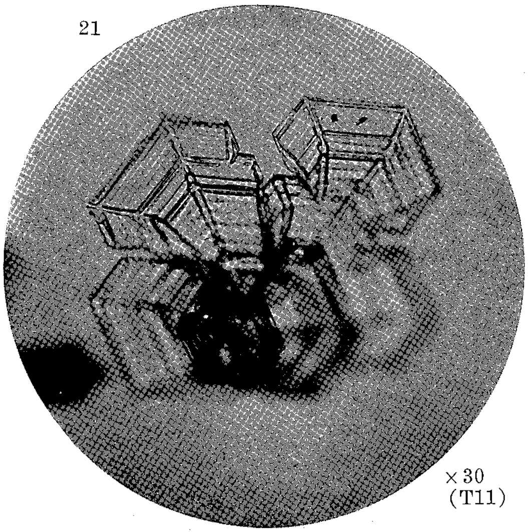

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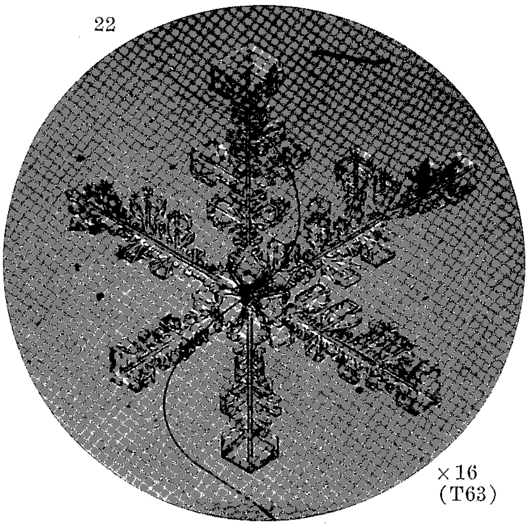

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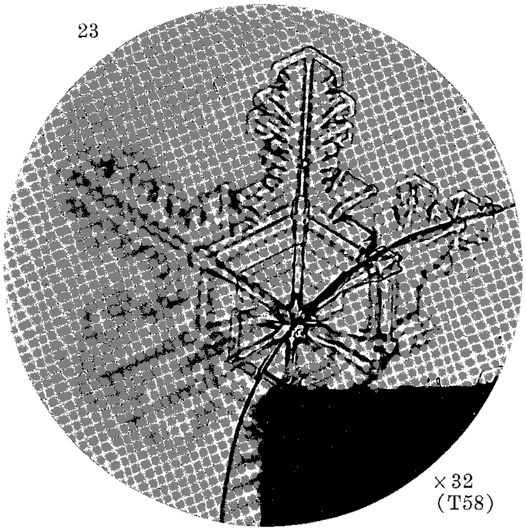

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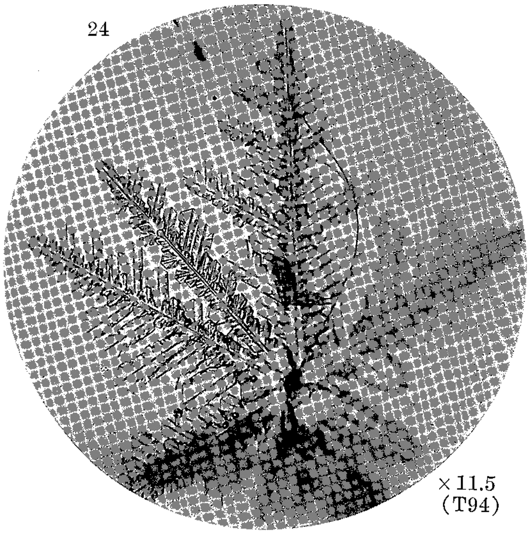
24



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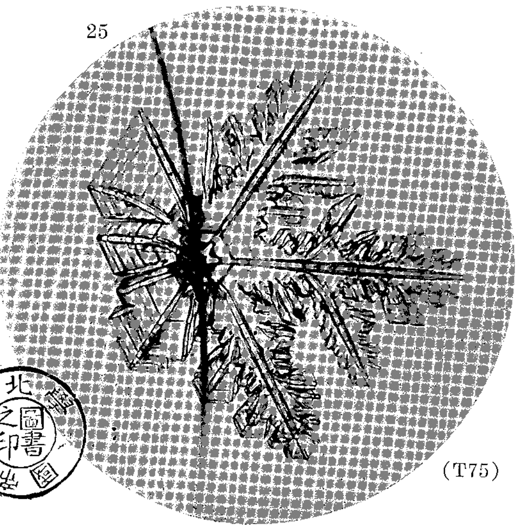
(T94)

25



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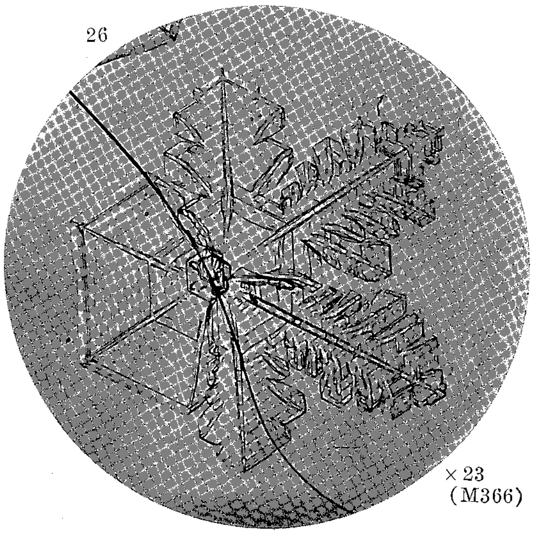

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(M366)

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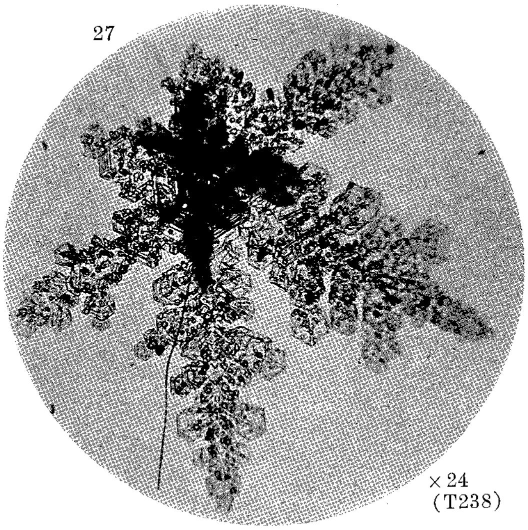

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(T238)

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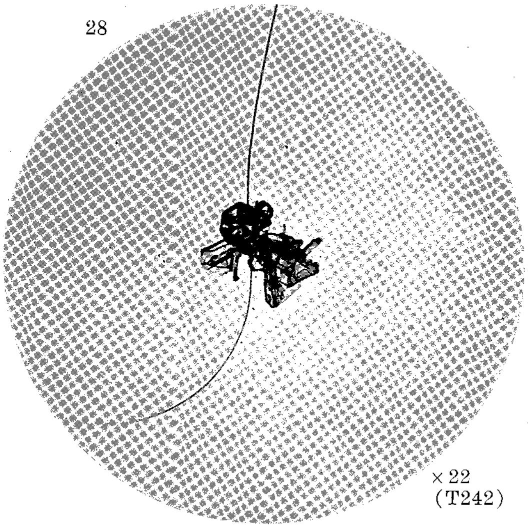

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(T242)

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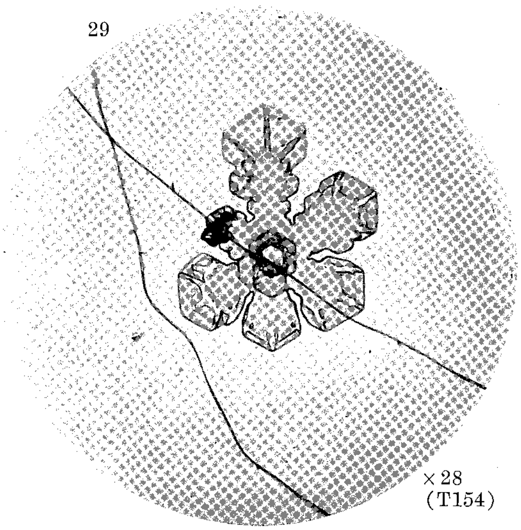

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(T154)

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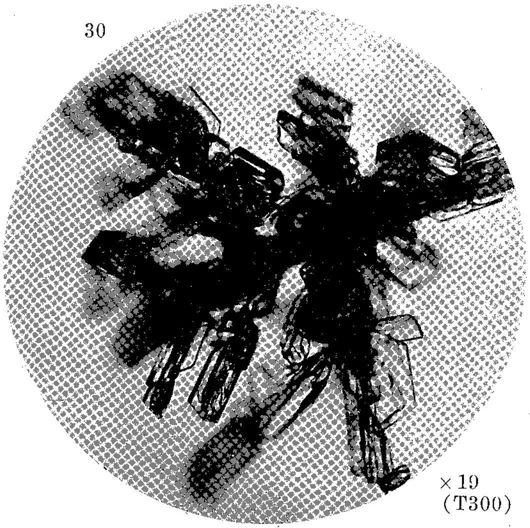
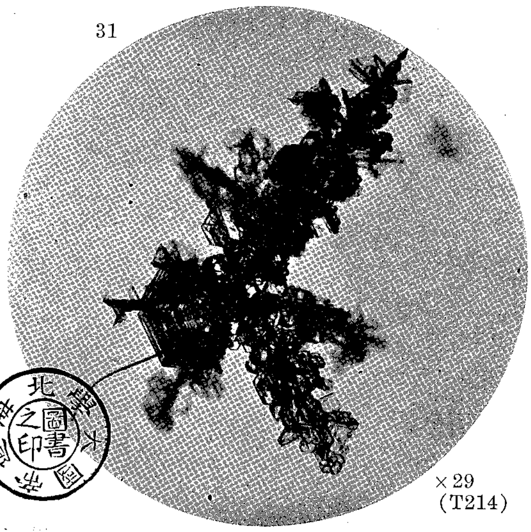


× 19
(T300)

31



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(T214)

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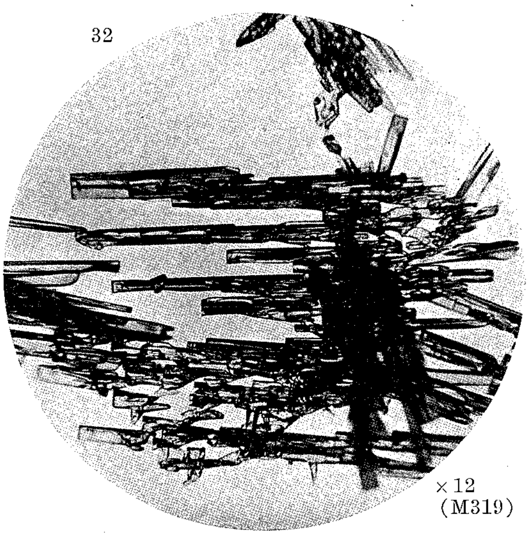

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(M319)

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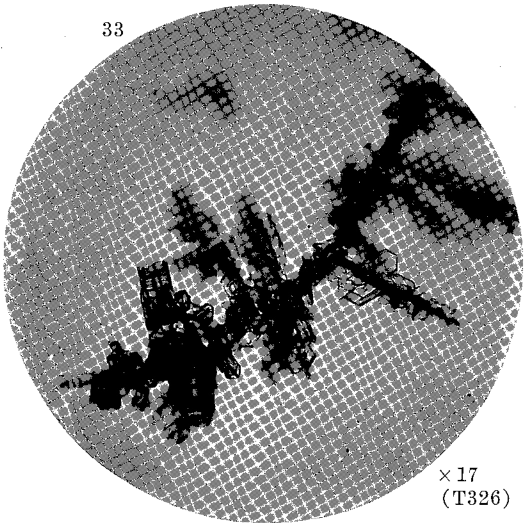

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(T326)

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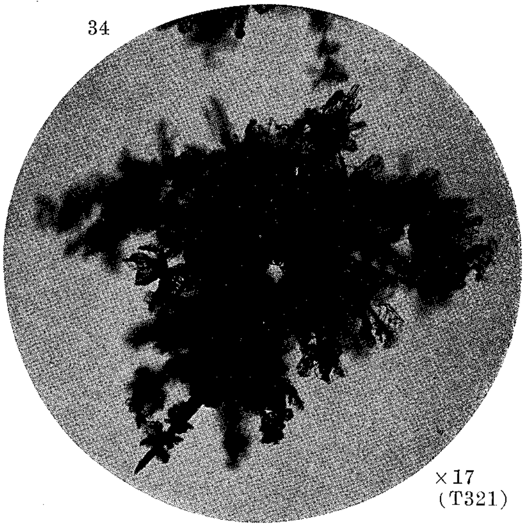

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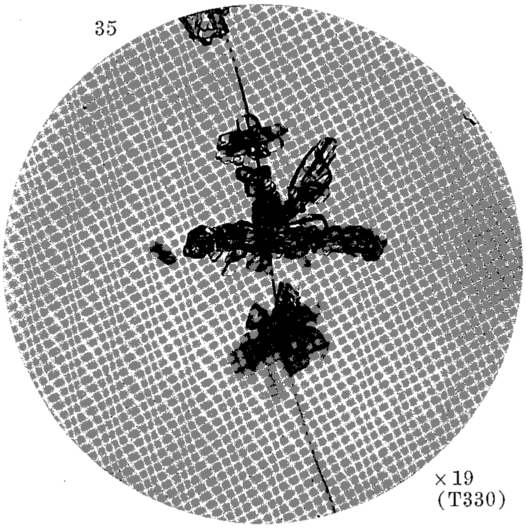
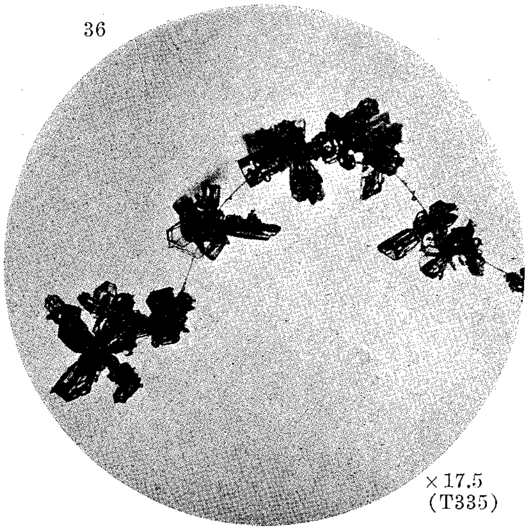


×19
(T330)

Compare with Photo. 35
of report No. 7.

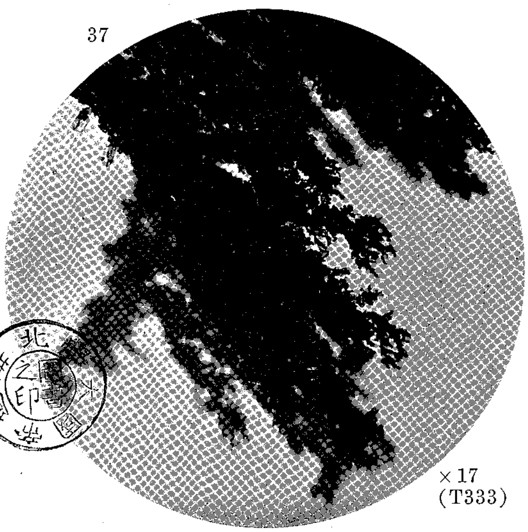
36



×17.5
(T335)

Compare with Photo. 37
of report No. 7.

37



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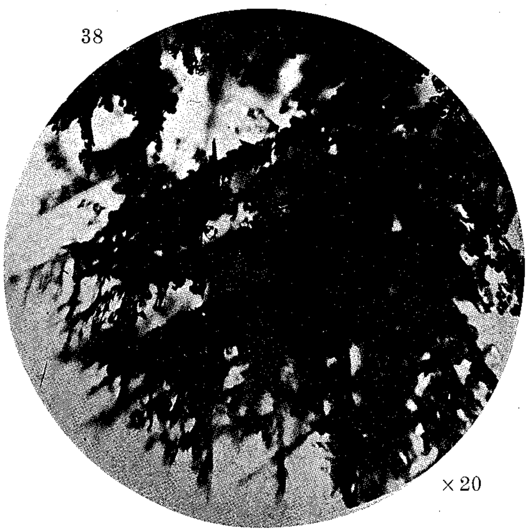
(T333)

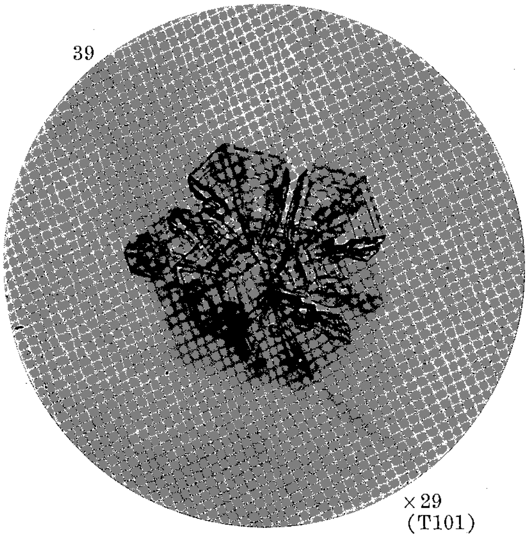
38



×20

Photographed by Mr. Nakata
in South Saghalien.

39



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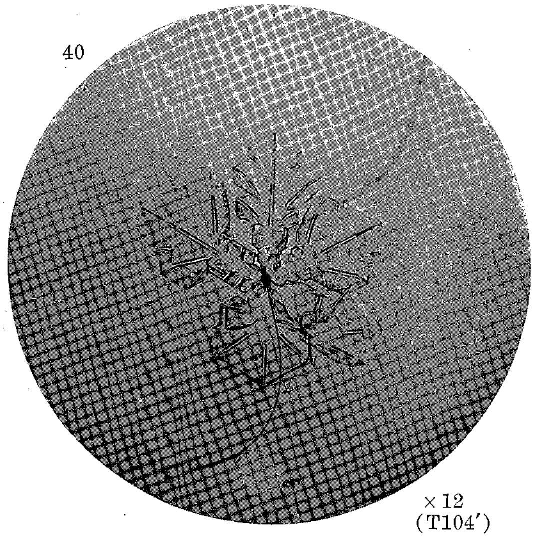

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(T104′)

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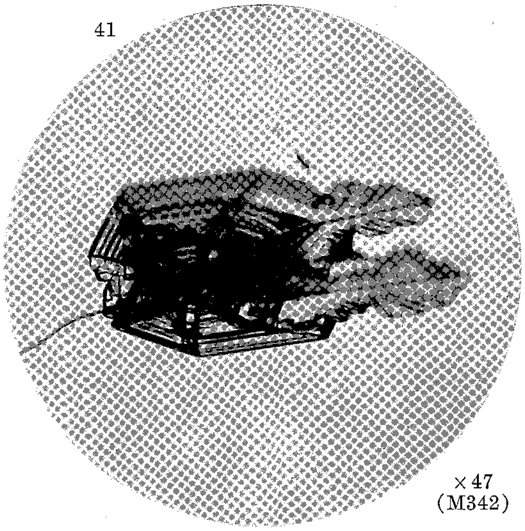

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(M342)

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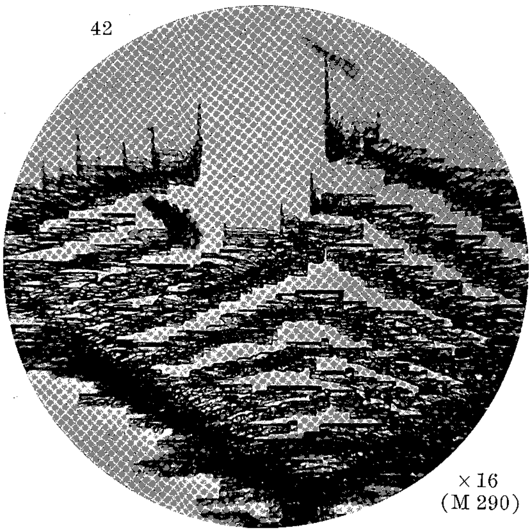

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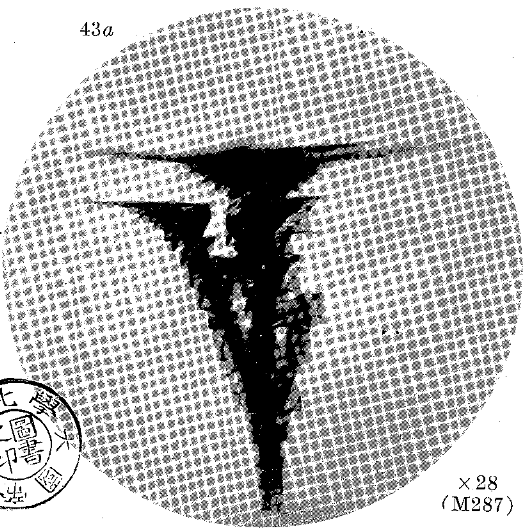
(M 290)

43*a*



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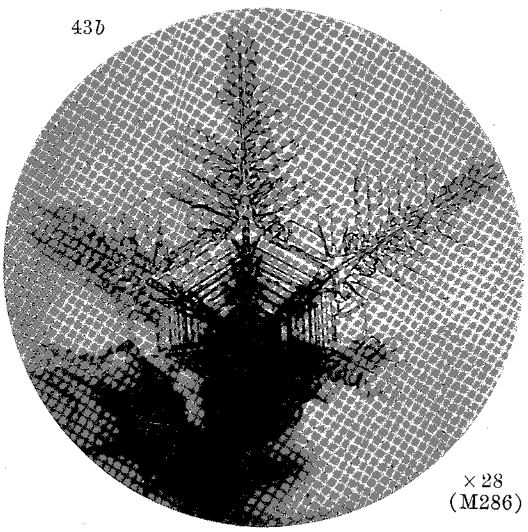
(M287)

43*b*



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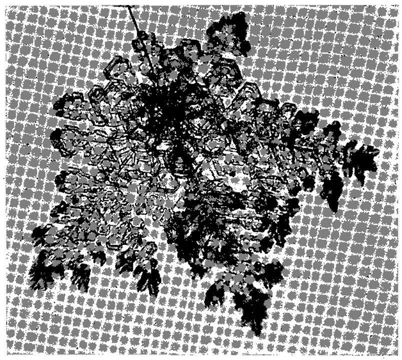
(M286)

44*a*



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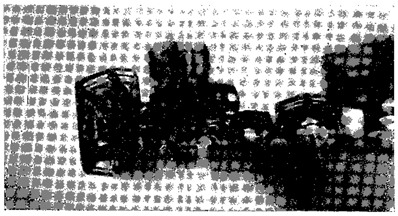
(M305)

44*b*



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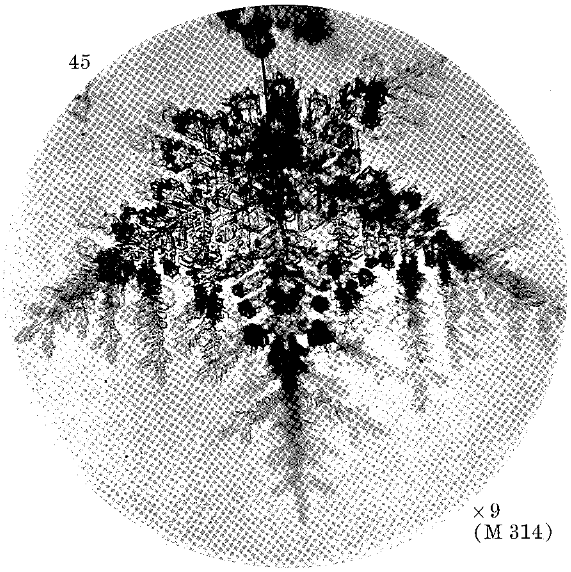
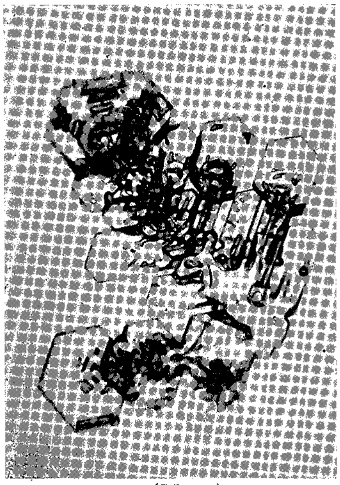


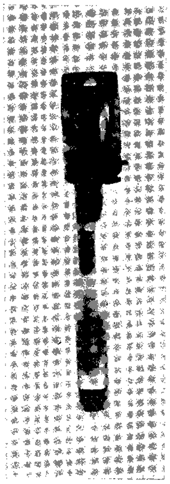
×9
(M 314)

46*a*



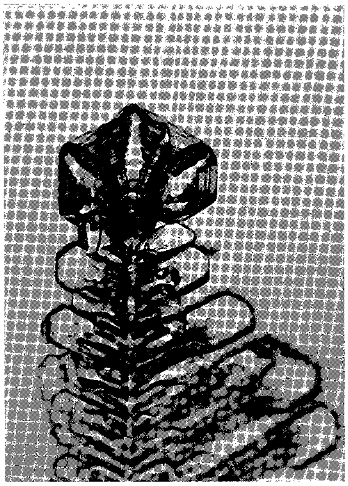
×39 (M329)

46*b*



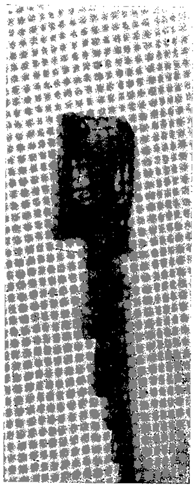
×39

47*a*



×34 (M334)

47*b*



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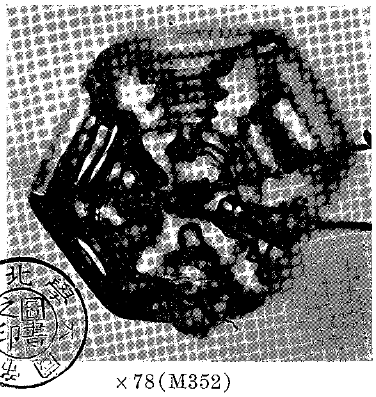
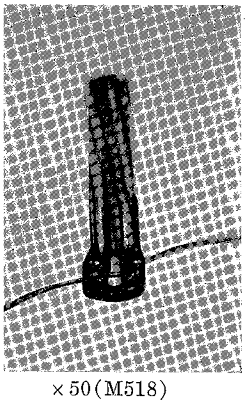


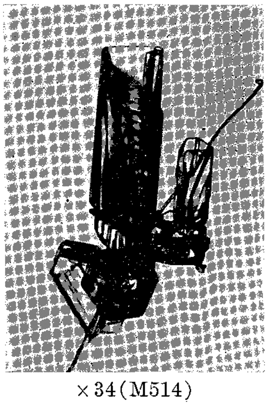
×78 (M352)

49



×50 (M518)

50



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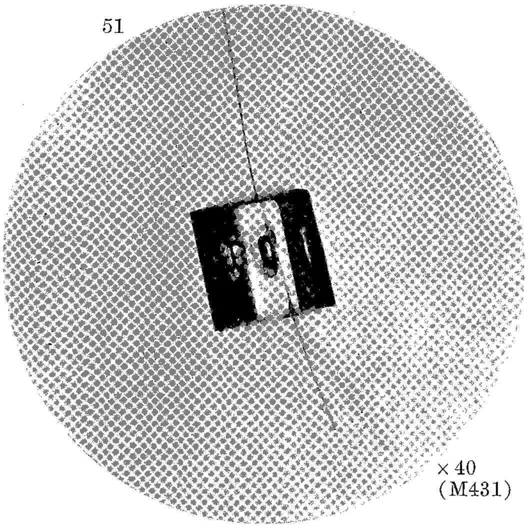

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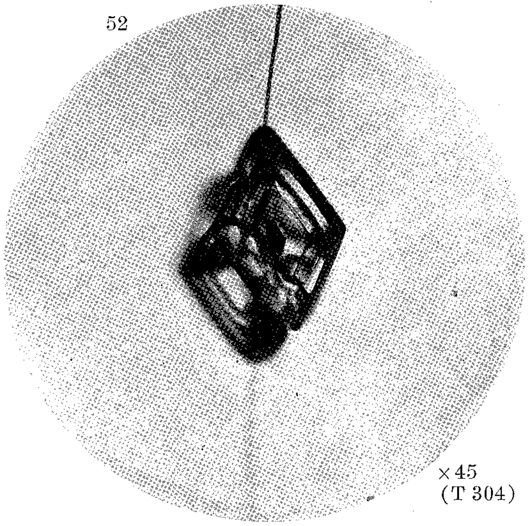
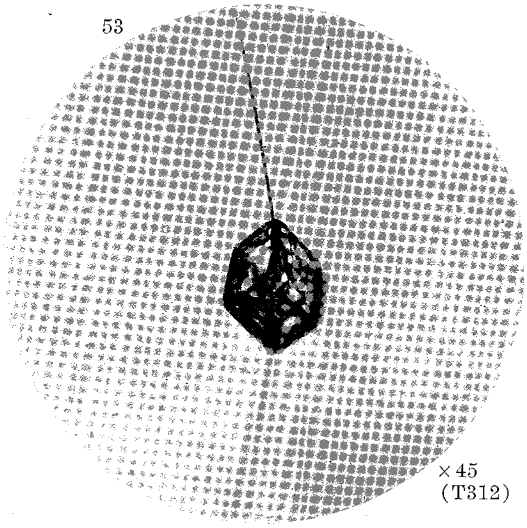


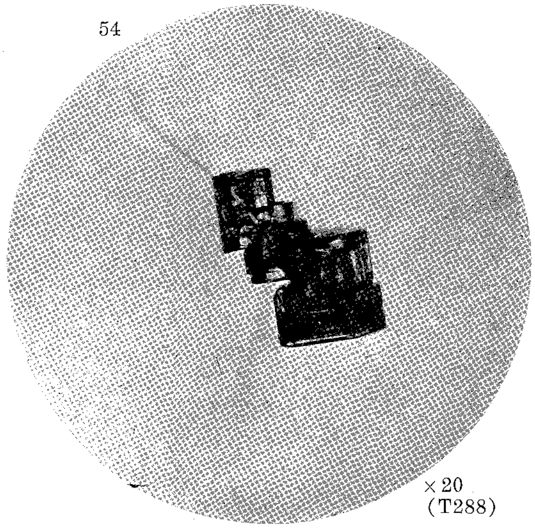
×45
(T 304)

53



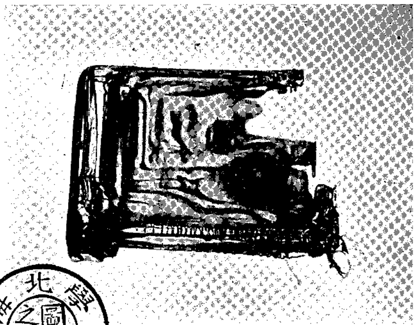
×45
(T312)

54



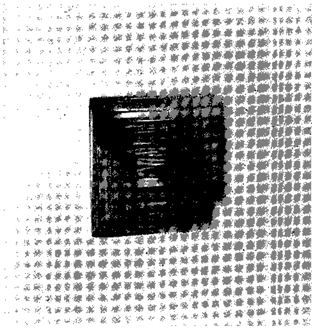
×20
(T288)

55



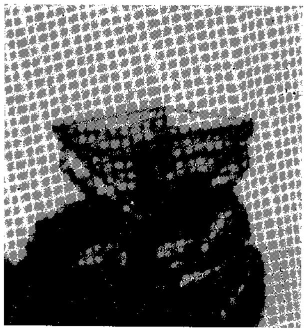
Photographed by Mr. Hatakeyama
at Toyohara. ×8

56



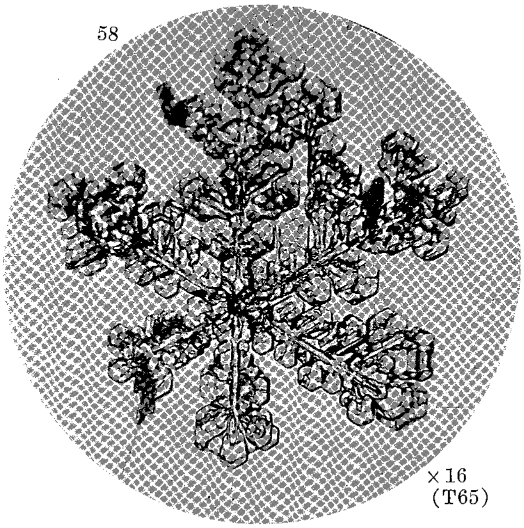
×26
(M76)

57



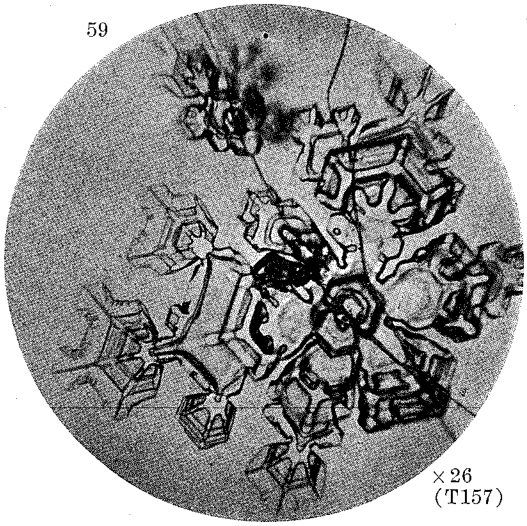
×134
(M386)

58



×16
(T65)

59



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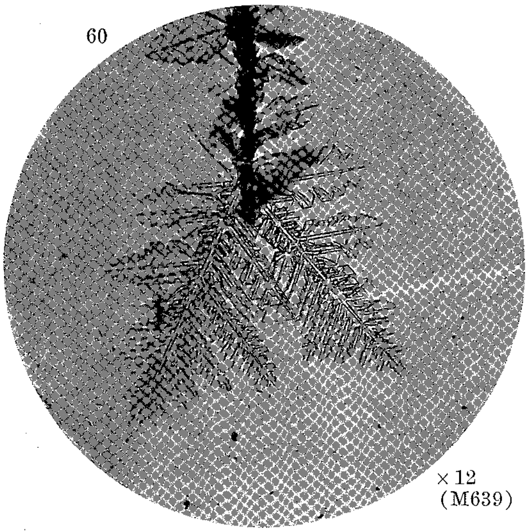
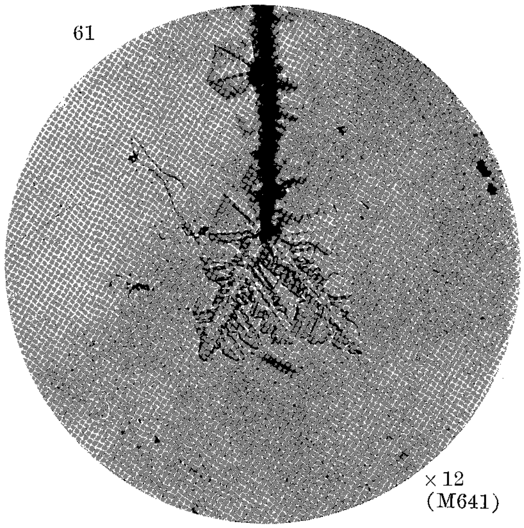
60



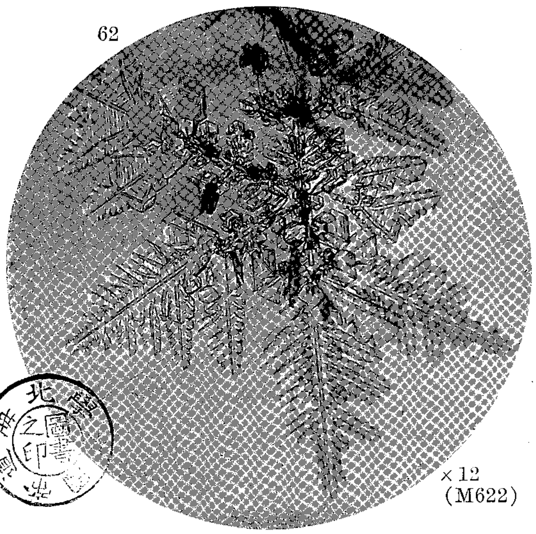
×12
(M639)

61



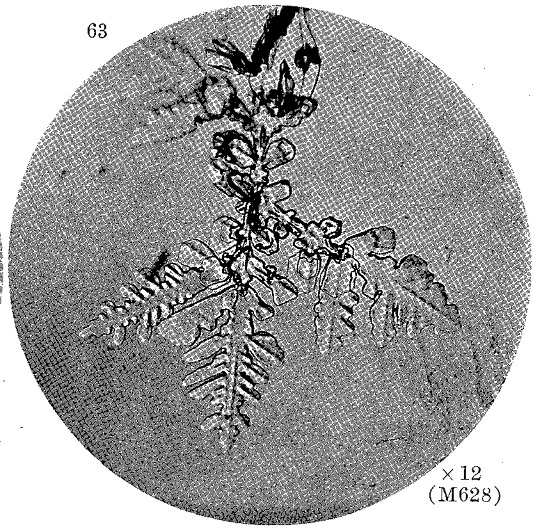
×12
(M641)

62



×12
(M622)

63



×12
(M628)